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(71) Applicant *(for all designated States except US)*: **ELECTRO SCIENTIFIC INDUSTRIES, INC.** [US/US]; 13900 NW Science Park Drive, Portland, OR 97229-5497 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **FAHEY, Kevin, P.** [US/IE]; 17 Leeson Village, Upper Leeson Street, Donnybrook, 4 Dublin (IE). **ZOU, Lian-Cheng** [CN/US]; 5801 SW Sheridan Ct, Portland, OR 97221 (US). **O'BRIEN, James, N.** [US/US]; 19015 Pinehurst Road, Bend, OR 97701 (US). **SUN, Yunlong** [US/US]; 7679 SW 194th Terrace, Beaverton, OR 97007 (US). **WOLFE, Michael, J.** [US/US]; 7400 SW Barnes Road # 223, Portland, OR 97225 (US).

(74) Agent: **LEVINE, Michael, L.**; Stoel Rives LLP, 900 SW Fifth Avenue, Suite 2600, Portland, OR 97204-1268 (US).

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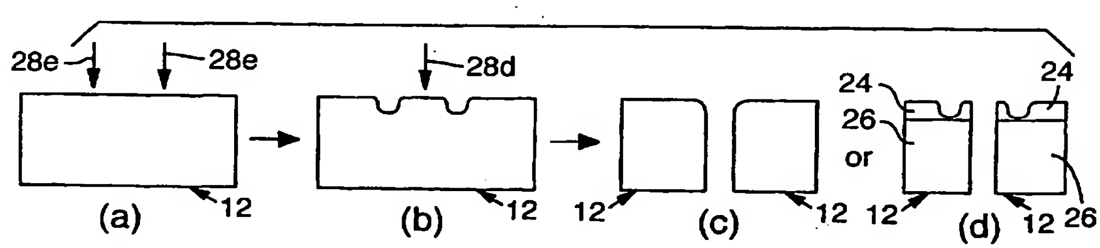
(54) Title: MULTISTEP LASER PROCESSING OF WAFERS SUPPORTING SURFACE DEVICE LAYERS



(57) Abstract: A multistep process (28) for dicing of, or drilling of vias in, workpieces (12), such as wafers, that support one or more layers (24) facilitates the optimization of laser or nonlaser processes (28) for each layer (24), including the substrate (26), to improve quality and throughput while reducing adverse affects to the other layers (24). An exemplary process employs a UV laser (14) for cutting through layers (24) that are transparent to IR or visible wavelengths and a different laser (14) or cutting blade for dicing the substrate (26) to minimize damage to the layers (24). A multistep processing technique can be used to mitigate or repair damage that occurs during dicing or drilling processes, to improve the lifetime of the mechanical saw, or to facilitate singulation of the greatest number of undammaged dies from a workpiece (12).

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MULTISTEP LASER PROCESSING OF WAFERS SUPPORTING SURFACE DEVICE LAYERS

Related Applications

[0001] This patent application derives priority from U.S. Provisional Application No. 60/301,701, filed June 28, 2001, from U.S. Patent Application No. 10/165,428, filed June 6, 2002, which claims priority from U.S. Provisional Application No. 60/297,218, filed June 8, 2001, from U.S. Patent Application No. 10/017,497, filed December 14, 2001, which claims priority from U.S. Provisional Application No. 60/265,556, filed January 31, 2001, and from U.S. Patent Application No. 09/803,382, filed March 9, 2001, which claims priority from U.S. Provisional Application No. 60/233,913, filed September 20, 2000.

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[0002] Not Applicable

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Technical Field

[0004] The invention relates to laser material processing and, in particular, to employing laser output to cut or form features in semiconductor wafers supporting one or more film layers or devices.

Background of the Invention

[0005] Most semiconductor and related products, such as transistors, diodes, light emitting diodes, microelectronic machine systems or micro-electro-mechanical systems (MEMS), planar waveguide structures, integrated circuits, or other microdevices, are manufactured contemporaneously in large batches on a large wafer. These wafers are

typically composed of Si, GaAs, GaP, InP, Ge, silicon carbide, sapphire, polymers, or other materials. The manufacture of these products or devices is most often performed using conventional fabrication techniques, such as, but not limited to, photolithography, oxidation, implantation, deposition, etching, epitaxial growth, and/or spin coating. Upon complete manufacture of these device-laden wafers, the individual devices must be separated or "singulated;" a process that is typically referred to as "dicing." In many singulation processes, the wafers are first separated in to rows of components, a process typically referred to as "slicing," but slicing and dicing may be used interchangeably The individual devices are referred to as "die" or "dice." The areas on a wafer in between active parts of adjacent dice are referred to as the "streets" or "dice lanes." The streets are limited to a minimum width because of the wafer material which is removed or destroyed during the dicing process. The wafer area that is completely removed by the dicing process is called a "kerf", and the rest of the street must accommodate any damage zone around the kerf and any manufacturing misalignment or dicing deviation from straightness of the kerf.

[0006] Conventionally, dicing is performed by the use of a wafer saw or by a technique of "scribe and break," where a wafer is notched to from a scribe line, often by a diamond point, and is then cleaved along the scribe line. Due to low yield issues, such as unpredictable propagation of microcracks as well as observable damage to devices, associated with scribe and break techniques, mechanical dicing saws have become the predominant tool for dicing wafers. Conventional slicing blades typically have a narrow dimension of about 50 to 200 μm along their cutting axis and produce cuts that are wider than the blades. The dicing blades are this wide to withstand stresses of making straight cuts through the hard and thick materials of conventional wafers. The wide cuts made by the mechanical cutting blades often significantly reduce the number of rows and columns of die that can be fit onto each wafer. Dicing blades also tend to wear relatively quickly such that the width of their cuts may vary over time In some cases, the blades can be inadvertently bent, and then they produce curved or slanted cuts or increased chipping. In addition, the dicing process also creates small chips as it creates sharp edges and sharp corners along singulation paths and makes the devices more susceptible to damage, particularly from external bumps. Dicing saws also tend to create microcracks that extend into the layers of devices from the kerf, reducing yields. In addition, microcracking may not be evident when the devices are tested, but then may propagate into the layers later to cause device failure, reducing the reliability of the devices and the equipment based on them. Although some microcracking may be avoided by slowing the mechanical sawing speed, microcracking is

very difficult, if not impossible, to avoid in some materials. Dicing saws also typically require the use of water as a lubricant and/or coolant, and the water can create problems or lower yields for certain types of materials or devices, such as MEMS.

[0007] A better method for dicing wafers is therefore desirable.

Summary of the Invention

[0008] An object of the present invention is, therefore, to provide a better method and/or system for cutting or drilling of wafers that support devices or layers of various materials on one or both sides of the wafer substrate.

[0009] Laser cutting is becoming an attractive alternative to the conventional mechanical cutting techniques. Some reasons for the consideration of laser dicing would be that lasers can cut curved die such as arrayed waveguide gratings (AWGs) from a wafer, unlike either of the two conventional techniques. In addition, lasers can often cut without the use of water, which is of great importance for the manufacture of devices which are water sensitive, such as MEMS. Lasers also offer the potential of the smallest street width available, due to a potentially very small kerf width and the possibility of very accurate alignment of the laser to the workpiece (wafer).

[0010] Lasers also can offer the ability to pattern wafers, creating features such as trenches or notches that can be made by scanning the laser across the surface and only cutting the film or partly through the wafer in contradistinction to mechanical saw dicing techniques that permit only throughcuts. The partial cutting techniques can be used to make features on die, or can also be used to perform laser scribing for a scribe-and-break process, for example.

[0011] Lasers also offer great potential for the drilling of vias through or into the film or substrate material. Such via drilling is of interest for reasons that may include, but are not limited to, allowing a ground to be contacted through the backside of a die, allowing die to be stacked on top of each other inside one package ("three-dimensional packaging"), or allowing devices to be mounted in a "flip-chip" BGA fashion such that the active devices would be facing up (with implications for MEMS or front-side cooling of integrated circuits or laser diodes). These vias can range from several microns in diameter up to several hundred, and the die thicknesses of interest vary from tens of microns to almost 1000 microns. Few production-worthy solutions currently exist for the drilling of such high-aspect ratio vias, and those such as plasma etching tend to be cumbersome, and expensive for equiptment and maintenance.

[0012] While laser processing capability has advanced greatly in the last few years due to advances both in available lasers and in process understanding, there are still some significant issues with the use of lasers for dicing, drilling, or patterning processes. Attempts may have been made to use infrared (IR) lasers to machine silicon or silicon oxides. IR wavelengths to a limited extent have been shown to machine these materials, and have been used successfully as laser scribing tools for marking die or for limited scribe and break applications. These lasers, however, tend to damage silicon, for example, such as by unpredictably cracking the silicon or oxide layers and by throwing permanent redeposited material (redep), such as melted slag, onto the top surface of the wafer and by creating a "melt lip" where the edge of the kerf pulls backward and up.

[0013] U.S. Pat. Nos. 5,593,606 and 5,841,099 ('099 Patent) of Owen et al. describe techniques and advantages for employing UV laser systems to generate laser output pulses within advantageous parameters to form through-hole or blind vias through at least two different types of layers in multilayer devices. These parameters generally include nonexcimer output pulses having temporal pulse widths of shorter than 100 ns, spot areas with spot diameters of less than 100 μm, and average intensities or irradiances of greater than 100 mW over the spot areas at repetition rates of greater than 200 Hz. The '099 Patent describes techniques that, after first processing a top metal layer, facilitate changing parameters, such as the power density, of the laser system output to process nonmetallic interlayers, including dielectric or reinforcement materials, in a manner that protects a bottom metal layer from damage.

[0014] Despite the foregoing, lasers have not until recently been employed successfully to dice or pattern silicon other types of semiconductor wafers or dice or pattern sapphire or other insulator wafers. U.S. Pat. Appl. No. 09/803,382 ('382 Application) of Fahey et al., describes a UV laser system and a method for separating rows or singulating sliders or other components. These methods include various combinations of laser and saw cutting directed at one or both sides of a wafer and various techniques for edge modification.

[0015] U.S. Patent Application No. 10/017,497 ('497 Application) of Baird et al., further describes using ultraviolet laser ablation to directly and rapidly form patterns with feature sizes of less than 50 μm in hard to cut materials, such as silicon. These patterns include: formation of very high-aspect cylindrical openings or blind vias for integrated circuit connections; singulation of processed dies contained on silicon wafers; and microtab cutting to separate microcircuits formed in silicon from parent wafer.

[0016] As discussed in detail in the '382 and '497 Applications, it is possible to determine many of several laser and optic processing parameters that can be optimized to cleanly cut a given material using a laser. These parameters may include, but are not limited to, wavelength, repetition rate, distance of new target material impinged by each sequential laser pulse (bite size), energy of each laser pulse, temporal pulse width, size of spot of laser system output, and spatial energy distribution within the laser spot. The parameters of choice for cutting a particular material can vary considerably, and the "process windows", the area of parameter space in which a given material can be cleanly ablated, differs for different materials. Even materials which appear to be the same (like various types of SiO_2 or SiON or Si_3N_4) can have very different optical and mechanical and thermal/ablative properties due to factors that may include, but are not limited to, different dopant, different stoichiometry, different deposition technique, different microstructure (due to the above or due to different underlayer, processing temperature profile, etc.), or different macrostructure (porosity, geometry, thickness). Thus, closely related materials may still have non-matching process parameters and process windows.

[0017] In many circumstances, the streets between the die on the wafers are covered with some or all of the overlying device layers, or the devices, themselves, are formed across the dice lanes. So, although the majority of the wafer thickness is usually taken up by the substrate material, it is desirable to first cut through the overlying device layers before cutting the substrate material and/or to pattern oxide or other device layers supported on a wafer before patterning or cutting the substrate material. Most devices are, however, made of several different materials, usually deposited or grown on top of the wafer in a build-up process. These materials may include, but are not limited to, metals, oxide dielectrics, nitrides, silicides, polymer dielectrics, and other semiconductor layers. Since in general two or more different materials do not respond in the same fashion to a particular set of laser parameters, applicants have determined that the layers supported by a wafer substrate are either relatively not well-processed at the substrate cutting parameters or are severely compromised during the laser cutting of the wafer. The resulting problems range from decreased cutting rate (if the laser is not efficient in cutting the overlayers) to the creation of a large damage region in the device layers in proximity to the laser processing area. For example, although IR lasers have had limited success to dice or scribe silicon, these lasers have been unable to cut through SiO_2 or other oxide layers on top of a silicon wafer.

[0018] Similarly, mechanical dicing techniques are well known to cause cracking, chipping and/or delamination in layers, especially layers that are brittle and/or have low adhesion. As layer stacks get more complicated, and with the introduction of more fragile materials such as oxide-based or other low-K dielectrics, this problem is expected to become worse, and certainly not less of an issue.

[0019] Accordingly, another object of the invention is to provide methods to dice, pattern, or drill a wafer supporting device layers by employing two or more different techniques or parameters to address different properties of the device layers and the wafer substrate material.

[0020] This multi-step process involves optimization of processes for at least two layers, and preferably such that the processing of any layer, including the substrate material layer, does not negatively affect the other layers. An exemplary embodiment employs one laser, such as a wavelength laser, used at different sets of parameters, such as different wavelengths or irradiances, to process the different layer or substrate materials. Another embodiment employs different lasers having different sets of parameters for processing the different layer or substrate materials, such as the use of a UV laser (e.g. at 266 nm) or an ultra fast laser for cutting device layers that are transparent in the IR or visible range and the use of an IR, visible, or UV laser (e.g. at 355 nm) to process the wafer material. A further embodiment employs one or more lasers to process the device layers and then employs a non-laser technique, such as a mechanical saw blade, to process most or all of the thickness of the wafer substrate material.

[0021] Still another embodiment entails covering the surface device layers of the wafer with a sacrificial layer such as photoresist or PVA; optionally removing a portion of the sacrificial layer to create uncovered zones over intended cutting areas; laser cutting the layers atop the wafer substrate to a width equal or slightly greater than that which will occur in the subsequent substrate cutting step; then cutting the wafer with a separate processing step or steps using different, wavelength, pulse width, fluence, bite size, and/or other laser processing parameters.

[0022] Additional objects and advantages of this invention will be apparent from the following detailed description of preferred embodiments thereof, which proceeds with reference to the accompanying drawings.

Brief Description of the Drawings

[0023] FIGS. 1A-1F are simplified and partly schematic views of several exemplary embodiments of laser systems suitable for multi-step laser processing in accordance with the present invention.

[0024] FIG. 2 is a simplified partly pictorial and partly schematic diagram of a more detailed exemplary laser system for performing multi-step laser.

[0025] FIG. 3 is a simplified pictorial diagram of an optional imaged optics module that may be used in any of the exemplary laser systems of FIG. 1.

[0026] FIG. 4 is a graph displaying the characteristic relationship between pulse energy and pulse repetition frequency of an exemplary laser employed in FIG. 2.

[0027] FIG. 5 is a simplified representation of a real time cut status monitor optionally employed by an exemplary laser system for performing multi-step laser processing in accordance with the present invention.

[0028] FIG. 6 depicts a cutting path having respective first and second transverse directions through which cutting speed is enhanced by an optional polarization tracking system.

[0029] FIG. 7 is a representative illustration of an ultraviolet transparent chuck on which semiconductor workpieces are placed for throughcut processing.

[0030] FIG. 8 is an enlarged plan view of an enlarged workpiece sequentially impinged by overlapping laser spots along a cutting path.

[0031] FIGS. 9A-9E are simplified side sectional views of a workpiece and its supported multiple layers undergoing process steps of a generic multi-step dicing or drilling process.

[0032] FIGS. 10A-10H are simplified side sectional views of a workpiece as it undergoes process steps of an exemplary laser rounding process.

[0033] FIGS. 11A-11F are simplified side sectional views of a workpiece as it undergoes process steps of an exemplary laser cutting process.

[0034] FIG. 12 is a simplified side section view of a workpiece undergoing a number of lines or rows of laser passes whose positions vary with distance from an edge.

[0035] FIG. 13 is a plan view of a portion of a row carrier supporting bowed and angled workpiece rows that can be diced by laser row defect compensation.

[0036] FIG. 14 shows a flow diagram of notching, rounding, and separating process with simplified side sectional views of a workpiece as it undergoes process steps.

[0037] FIG. 15 shows a flow diagram of a rounding and separating process.

[0038] FIG. 16 shows a flow diagram of an alternative rounding and separating process.

[0039] FIG. 17 is a simplified representation of a segmented cutting profile that may be employed to facilitate laser cutting in accordance with the present invention.

[0040] FIG. 18 is a simplified representation of an alternative segmented cutting profile.

[0041] FIG. 19 is a simplified representation of an alternative segmented cutting profile.

[0042] FIG. 20 is a simplified representation of an alternative segmented cutting profile.

[0043] FIG. 21 is a simplified representation of an alternative segmented cutting profile.

[0044] FIG. 22 is a simplified representation of an alternative segmented cutting profile.

[0045] FIG. 23 is a simplified representation of an alternative segmented cutting profile.

[0046] FIG. 24 is a representative illustration of a trench pattern formed by segmented cutting processing of silicon.

[0047] FIG. 25 is a representative illustration of patterning of a MEMS device by a segmented cutting process on a semiconductor wafer.

[0048] FIG. 26 is a representative illustration of an AWG device fabricated by a segmented cutting process on a semiconductor wafer.

Detailed Description of Preferred Embodiments

[0049] Quality and/or throughput advantages for processing workpieces, such as wafers having a substrate material, that support devices or film layers of different materials can be facilitated by processing at least two of the materials in different manners. A laser process may be used to process one or more layers while a mechanical saw blade may be used to process the remaining layer or layers. Different sets of laser parameters may be employed to process different respective layers. Specific examples of these approaches will be presented in greater detail after the following discussion of various aspects of laser systems advantageous for implementing the present invention.

[0050] FIGS. 1A-1F (generically FIG. 1) depict several simplified schematic embodiments of laser systems 10a-10f (generically laser system 10) showing lasers 14a-14f (generically laser 14) and optics 58a-58f (generically optics 58) that may be employed for implementing different embodiments of the present invention to process workpieces 12a-12f (generically workpiece 12) that include a substrate that supports one or more layers of different materials. FIG. 2 depicts a more detailed embodiment of one exemplary laser system 10, and FIGS. 9A-9E (generically FIG. 9) depict exemplary sequential processing steps 28a-28d (generically processing steps 28) for processing layers 22 and 24 (generically layers 24) and substrate 26.

[0051] With reference to FIGS. 1, 2, and 9, laser system 10a of FIG. 1A employs one laser 14a and one set of optics 58a to process a workpiece 12a supported on a stage. Laser system 10a may be preferred for embodiments where the single laser 14a is employed to supply at least two steps 28 using sets of different parameters, such as different wavelengths, to process at least two different respective materials such as two different device layers 24 or device layer(s) 24 and the substrate layer 26. Alternatively, laser system 10a may be preferred where the single laser 14a is employed to process one or more materials such as device layers 24 with one set of parameters and the remaining layers 24 and/or substrate 26 is processed by one or more sets of other parameters from the same laser or by a mechanical dicing blade.

[0052] With reference to FIG. 1B, laser system 10b employs two lasers $14b_1$ and $14b_2$ with distinct sets of optics $58b_1$ and $58b_2$ along two separate beam delivery paths 20 impinging upon the same workpiece 12b. Lasers $14b_1$ and $14b_2$ provide laser system outputs 32 with respectively different sets of parameters that are selectively employed to process different respective layers 24 and/or substrate 26 in different process steps 28. Lasers $14b_1$ and $14b_2$ are preferably employed in sequential applications but may also be employed simultaneously to process a given layer 24 or substrate 26. All of one type of material across an entire workpiece 12b may be processed with laser $14b_1$ before laser $14b_2$ is employed to process a second type of material, or laser $14b_2$ may begin operation while laser $14b_1$ is still in operation. Variants of this embodiment include having the laser system outputs 32 impinge at adjacent positions with the ability to move the workpiece 12 between the two positions. An alternative application is to process layers 24 with identical parameters with lasers $14b_1$ and $14b_2$ and then to process the remaining layers 24 with lasers $14b_1$ and $14b_2$ at another set identical parameters or by a mechanical saw.

[0053] With reference to FIG. 1C, laser system 10c employs two lasers $14c_1$ and $14c_2$ with distinct sets of optics $58c_1$ and $58c_2$ along two separate beam delivery paths 20 impinging upon the same workpiece 12c from opposite sides of workpiece 12c. Lasers $14c_1$ and $14c_2$ may provide laser system outputs 32 with the same set of parameters to increase the throughput by simultaneously processing corresponding one or more layers 24 and/or substrate 26 from opposite sides of the workpiece, such as in case where a wafer has a coating or device layers 24 on each side, or by processing simultaneously the different materials exposed on each side. Lasers $14c_1$ and $14c_2$ may be adjustable to provide corresponding different processing steps having different sets of parameters for processing

different layers 24 and/or substrate 26. Alternatively, lasers $14c_1$ and $14c_2$ may provide laser system outputs 32 with respectively mutually exclusive sets of parameters that are selectively employed to process different respective layers 24 and/or substrate 26. Laser system 10c may be adapted for flipping or rotating the workpiece 12 to present an opposite side for subsequent processing by a different laser 14c at a different set of parameters.

[0054] With reference to FIG. 1D, laser system 10d employs two lasers $14d_1$ and $14d_2$ employing a single set of optics 58d along a single beam delivery paths impinging upon the same workpiece 12d. Lasers $14d_1$ and $14d_2$ may provide laser system outputs 32 with the same set of parameters to increase the throughput of processing one or more layers and may be adjustable to provide corresponding different sets of parameters for processing different layers 24 and/or substrate 26. Alternatively, lasers $14d_1$ and $14d_2$ may provide laser system outputs 32 with respectively mutually exclusive sets of parameters that are selectively employed to process different respective layers 24 and/or substrate 26. Lasers $14d_1$ and $14d_2$ may also be employed simultaneously to process a given layer 24 and/or substrate 26.

[0055] With reference to FIG. 1E, laser system 10e employs two lasers $14e_1$ and $14e_2$ with distinct sets of optics $58e_1$ and $58e_2$ along two separate beam delivery paths 20 impinging upon different workpieces $12e_1$ and $12e_2$ on separate stages 36. Lasers $14e_1$ and $14e_2$ provide laser system outputs 32 with respectively different sets of parameters that are selectively employed to process different respective layers. Lasers $14e_1$ and $14e_2$ are preferably employed in sequential process steps 28 but may also be employed simultaneously to process a given layer 24 and/or substrate 26. All of one type of material across an entire workpiece $12e_1$ is preferably processed with laser $14e_1$ before being transferred for processing by laser $14e_2$ to process a second type of material. In one embodiment, laser $14e_1$ processes surface device layer(s) of workpiece $12e_1$ while laser $14e_2$ processes the substrate material of workpiece $12e_1$ and the workpieces 12e are then flipped during transfer for processing by the other laser 12e.

[0056] With reference to FIG. 1F, laser system 10f is a variation of laser system 10a that employs an external cavity harmonic generation system 15 through which laser output 16 can be diverted or that can be omitted from an optical path 20 to provide different wavelengths for processing different layers 24 and/or substrate 26.

[0057] Several exemplary embodiments employ only one laser type, such as shown in FIGS. 1A and 1F, used at different sets of parameters to process the different layers 24 or substrate 26. One example employs the use of the same laser 14 at the same wavelength but

different other parameters to process different layer materials or substrate materials, such as to process a workpiece having silicon dioxide supported by a silicon substrate wafer. Applicants have determined that the silicon underneath a silicon dioxide layer 24, is melted, evaporated or ionized by a high intensity UV laser system output 32 very quickly but that the same intensity causes breaks and/or makes very bad cracks in the oxide layer. To avoid this damage, parameters that include low intensity and high speed are used as a first step 28 to make openings along the cutting path 112 (FIG. 5) on the silicon dioxide layer 24 as an exit for ejected silicon, and then parameters that include high intensity at the same wavelength are applied to the silicon substrate 26 to singulate the workpiece 12 into dies. Exemplary parameters for the first step 28 may include 0.4 W and/or 35 J/cm^2 (preferably less than 50 J/cm^2) at 30 kHz with scan speed 100 mm/s. The parameters can be modified for different materials and/or coating techniques of a layer 24 or layers 24, and/or different materials, coating techniques and/or crystal orientation of bottom layers 24 and/or substrate 26. For example, the parameters for an identical material silicon dioxide deposited with different techniques may be processed with very different processing parameters. The second step 28 may include, for example, parameters with some of the higher intensities and/ or fluence greater than 240 J/cm^2 and/or other parameters disclosed in connection with subsequent discussions. The laser system output 32 for either laser step 28 in the above or any of the following examples may be applied by a traditional scanning process or by a segmented cutting process described later herein, unless specifically specified to the contrary. In addition, it may be desirable to use two or more adjacent or partly overlapping cutting paths 112 to make a wide kerf through any or all of the layers 24 or the substrate 26. Alternatively, a defocused laser spot or a top hat shaped laser beam can be used to get desired kerf widths. In particular, it may be desirable to make a wider notch through a top layer 24 and gradually narrower notches through deeper layers 24 and the substrate 26, such that subsequent passes 132 can be contained completely within the notch opened in the preceding upper layer 24. It may also be useful to use different parameters for various passes 132 in one notching step 28 to tailor the notch geometry, including sidewall angle, or to increase throughput.

[0058] Another example that may employ the same laser 14 at the same wavelength but different parameters is removal of a sacrificial layer 22 before dicing through device layers 24 and the substrate 26. A sacrificial layer 22 may be coated for protecting the devices from debris creating during laser dicing. Typical materials for a sacrificial layer 22 may include, but are not limited to, photoresist, PVA, silicon dioxide, silicon nitride. Semiconductor manufacturers prefer sacrificial layer materials that are easily removed by solvents, water, ash

or etch techniques after dicing. These materials are often "soft" for laser applications and are easy to burn or carbonize at preferred dicing parameters, can cause device failures and low yields, and hard to clean off once burned or carbonized. The sacrificial layer 22 is thus preferably removed at gentler parameters to create uncovered zones over intended cutting streets, to a width equal to or greater than that which will occur in the subsequent substrate cutting step 28 , before laser dicing parameters are applied. In one example, a PVA layer 22 covering devices supported on a sapphire substrate 26 is removed along the dicing streets with low pulse energy and high scanning speed before the device and sapphire are singulated at higher pulse energy at the same wavelength. Different laser pulse width, bite size, or other laser processing parameters can also be employed for the two process steps 28. Exemplary process parameters for the first step 28 include 3.55 W at 65 kHz with a scan speed 400 mm/s. Skilled persons will appreciate that parameters can be modified to suit sacrificial layers 22 of different materials.

[0059] Another embodiment employs a single laser 14 that is switchable between at least two different wavelengths to provide different sets of parameters for processing the different layer or substrate materials. In one example, a switchable UV laser 14 employs 266 nm laser system output 32 to process alumina and 355 nm laser system output 32 to process AlTiC. In another example, a switchable solid-state laser 14 employs a UV wavelength for cutting device layers 24 that are transparent in the IR or visible range and employs IR or visible wavelengths to process the wafer substrate material. In particular, a UV wavelength, such as third or fourth harmonics, is used to cut ceramic, glass, polymer or metal films that may be supported on the top or bottom surfaces of the wafer substrate 26, while a visible or IR wavelength, first or second harmonics, is used to cut through the substrate material after the layers 24 have been cleared away. In another embodiment, UV is used in the first step and 355 nm or 532 nm is used in the second step.

[0060] A further embodiment employs different lasers 14 having different sets of parameters for processing the different layer or substrate materials, with each laser 14 being dedicated to process particular layer(s) 24 or substrate(s) 26 at respectively different laser parameters. These lasers 14 may propagate laser output 16 along common or discrete optical paths 20. Examples of laser systems 10 for implementing these embodiments include, but are not limited to system designs shown in FIGS. 1B, 1C, 1D, and 1E. In one example, some applications described above may be effected by distinct lasers 14 operating at the same wavelengths at different parameters, and other the applications described above may be effected by distinct lasers 14 operating at different wavelengths. In particular, one laser 14

may be used to generate one or more UV wavelengths and another laser 14 may be used to generate IR and/or visible wavelengths. For some applications where versatility is desired both types of lasers 14 are solid-state lasers 14. In other applications, the UV laser 14 may be an excimer and/or the IR laser 14 may be a CO_2 laser 14, for example.

[0061] Yet another embodiment employs one or more lasers 14 to process one or more device layers 24 and then employs one or more non-laser techniques, such as cutting with a mechanical saw blade, to process most or all of the thickness of the wafer substrate material. In one example, any of the above-described lasers 14 or combinations of lasers 14 may be employed to remove all of one or more device layers 24, such as metals, oxides, polymers, or other soft materials from the streets before singulating workpieces 12 with a mechanical saw, such that during subsequent dicing with a saw blade, the blade only makes contact with the substrate material. This method prevents blade degradation due to the presence of a softer material on the more brittle substrate material. Benefits of this technique may include, but are not limited, to improved lifetime of saw blades or the reduction of damage to the edges of the cut in the substrate 26 due to a contaminated blade. This technique will also be of particular use when dicing wafers with metallization in the dice lanes, such as that due to the presence of test devices or ESD shunts, or when dicing wafers that support a polymer dielectric material or some of the low-K materials that are presently on the market. Saw cutting instead of laser cutting may be used to remove the substrate 26 after any of the above described methods employed for removal of one or more device layers 24. It may also be desirable to notch the substrate 26 with a laser to a limited depth before employing a nonlaser technique, and/or it may be desirable to apply laser output 32 to the cut after nonlaser processing.

In a particular example, the width of layer removal is slightly wider than the width of saw dicing. Such a wide cutting line can be made with 3-7 adjacent or partly overlapping cutting lines of 20-40 μm kerf width (an exemplary total width is approximately 120 μm, but this width can be adjusted to suit particular applications) at 1.16 W at 20 kHz with scan speed 100 mm/s. For higher throughput, one cutting line of appropriate size can be applied such as with a top hat beam shaper. The processing parameters are exemplary only and can be adjusted to suit the to the characteristics of the layer and substrate materials. In an alternative to making wide notches in applications where saw blade degradation is not a factor, it may be desirable to make laser notches through one or more layers 24 and/or the top of the substrate 26 on either side of a prospective saw cut to prevent delamination or any type of crack propagation.

[0062] Mechanical saw dicing can for example induce microcracking, which can cause failures of devices and low yields. Some microcracks do not extend into device area immediately, but the devices can fail anytime when microcrack eventually extends into the device area. This causes poor reliability due to the uncertainty of the lifetime of the devices. The geometrical modification, such as by making two trenches near the edges of streets before mechanical saw dicing, terminates microcrack propagation at the edge of the trenches. In some examples, 0.2 W at 30 kHz with a scan speed of 30 mm/s is used to process low-k materials, and 1.16 W at 20 kHz with a scan speed of 100 mm/s for metals, oxides, and polymers. The laser processing parameters can be modified to suit the characteristics of the materials.

[0063] The notches may extend only to the bottom of the layers 24 or may extend further into the substrate material depending on the damage mode which is anticipated during the dicing process. For example, if the layers 24 are delaminating during the subsequent cutting process, the notches need only go below the interface of interest. If the substrate material is being damaged during the subsequent cutting process, it may be of interest to make the notches penetrate more deeply into the substrate material.

[0064] Another embodiment of the invention includes laser processing performed at the same or different parameters after the notching or trenching or removal of the surface layers 24 in order to correct any damage that may have been created during the laser processing steps 28 which cut through the layers. This technique may be done before or after the dicing of the substrate 26.

[0065] Another embodiment of the invention includes laser processing done at different parameters after the substrate dicing step in order to correct any damage that may have been created during the substrate dicing step. For example, the laser system output 32 can be used to melt edges of layers 24 in order to seal the edges and eliminate any cracks or crack initiation sites that may have originated. The laser system output 32 may also be used to round the corner of the diced edge later described herein to eliminate any sharp edges or chips which may have occurred during dicing.

[0066] While much of the description uses Si and SiO_2 as examples for the substrate 26 and layer 24, respectively, creation of semiconductor and related devices employ a wide variety of wafer types that use different substrate materials. These substrate materials include, but are not limited to, Si, GaAs, GaP, InP, sapphire, SiGe, silicon on sapphire (SOS), silicon on insulator (SOI), and various types of ceramic material such as AlTiC. Layer types

include but are not limited to various metals, oxides, nitrides, polymers, epitaxial or amorphous or polycrystalline semiconductor materials. As such, there is a wide range of combinations of lasers and laser/optic process parameters that can be used for the multi-step laser dicing or drilling of all such devices.

[0067] Although the detailed description is presented herein by way of example to a Q-switched, DPSS UV laser 14 and such laser 14 is preferred for at least one of the lasers 14 in many of the embodiments and applications, skilled persons will appreciate that many other types of lasers 14 may be useful for specific combinations of layers and/or substrates. These laser types include, but are not limited to, excimer, CO_2, Nd:YAG, Nd:YLF, Vanadate (or harmonic generated versions of the previous three), Ar-Ion, Cu vapor. These individual lasers 14 are commercially available and well known to skilled practitioners. Combinations including heads of any of these laser types may be employed on the platform of the positioning system 30 or other positioning system platforms to address specific combinations of layers 24 and/or substrates 26. The wavelengths available from these various lasers range from the UV, through the visible spectrum and into IR.

[0068] Although a preferred laser for patterning or trenching surface layers such as SiO_2 is a UV Q-switched, solid-state laser 14 providing laser system output 32 at a bite size of between about 1 to 7 μm, other UV lasers, which offer other output parameters, including excimers can be employed for those materials that process well UV wavelengths. In a particular embodiment, an ultra fast pulse laser can be used to process a layer 24 or layers 24, followed by other laser or nonlaser techniques for completing the dicing. Such combination permits the excellent cut quality afforded by an ultra fast pulse laser, but avoids its slow speed for processing the thick, hard to cut materials. Although a Q-switched, solid-state laser 14 providing imaged, shaped output may be preferred for cutting materials that process well with visible or infrared wavelengths, many other lasers such as non-Q-switched lasers 14 or CO_2 lasers 14 may be employed.

[0069] For the cutting or processing of layers 24 or substrates 26 where positionable laser system output 32 is desirable, an exemplary laser system 10 as shown in FIG. 2 utilizes a compound beam positioning system 30 that can be employed for performing cutting, such as trenching, slicing, or dicing, or feature creation, such as via drilling, in semiconductor workpieces 12 that support one or more surface device layers or films in accordance with the present invention. With reference to FIG. 2, an exemplary embodiment of a laser system 10 includes a Q-switched, diode-pumped (DP), solid-state (SS) UV laser 14 that preferably

includes a solid-state lasant such as Nd:YAG, Nd:YLF, or $Nd:YVO_4$. Laser 14 preferably provides harmonically generated UV laser output 16 of one or more laser pulses at a wavelength such as 355 nm (frequency tripled Nd:YAG), 266 nm (frequency quadrupled Nd:YAG), or 213 nm (frequency quintupled Nd:YAG) with primarily a TEM_{00} spatial mode profile.

[0070] In a preferred embodiment, laser 14 includes a Model 210-V06 Q-switched, frequency-tripled Nd:YAG laser, operating at about 355 nm with 5 W at the work surface, and commercially available from Lightwave Electronics of Mountain View, California. This laser has been employed in the ESI Model 2700 micromachining system available from Electro Scientific Industries, Inc. of Portland, Oregon. In an alternative embodiment, a Lightwave Electronics Model Q301or Q302) Q-switched, frequency-tripled Nd:YAG laser, operating at about 355 nm may be employed in order to employ high energy per pulse at a high pulse repetition frequency (PRF). Details of another exemplary laser 14 are described in detail in U.S. Pat. No. 5,593,606 of Owen et al. Skilled persons will appreciate that other lasers could be employed and that other wavelengths are available from the other listed lasants. Although laser cavity arrangements, harmonic generation, and Q-switch operation, and positioning systems 30 are all well known to persons skilled in the art, certain details of some of these components will be presented within the discussions of the exemplary embodiments.

[0071] Although Gaussian may be used to describe the irradiance profile of laser output 16, skilled persons will appreciate that most lasers 14 do not emit perfect Gaussian output 16 having a value of M^2=1. For convenience, the term Gaussian is used herein to include profiles where M^2 is less than or equal to about 1.5, even though M^2 values of less than 1.3 or 1.2 are preferred. A typical optical system produces a Gaussian spot size of about 10 μm, but this may easily be modified to be from about 2-100 μm.

[0072] Despite the substantially round profile of laser system output pulse 32, improved beam shape quality may be achieved with an optional imaged optics module 62 whereby unwanted beam artifacts, such as residual astigmatism or elliptical or other shape characteristics, are filtered spatially. With reference to FIG. 3, image optics module 62 may include an optical element 64, a lens 66, and an aperture mask 68 placed at or near the beam waist created by the optical element 64 to block any undesirable side lobes and peripheral portions of the beam so that a precisely shaped spot profile is subsequently imaged onto the work surface. In an exemplary embodiment, optical element 64 is a diffractive device or

lens, and lens 66 is a collimating lens to add flexibility to the configuration of laser system 48.

[0073] Varying the size of the aperture to match the properties of optical element 64 can control the edge sharpness of the spot profile to produce a size-specified, sharper-edged intensity profile that should enhance the alignment accuracy. In addition, with this arrangement, the shape of the aperture can be precisely circular or also be changed to rectangular, elliptical, or other noncircular shapes that can be aligned parallel or perpendicular to a cutting direction. The aperture of mask 68 may optionally be flared outwardly at its light exiting side. For UV laser applications, mask 68 in imaged optics module 62 preferably comprises sapphire. Skilled persons will appreciate that aperture mask 68 can be used without optical elements 64 and 66.

[0074] In an alternative embodiment, optical element 64 includes one or more beam shaping components that convert laser pulses having a raw Gaussian irradiance profile into shaped (and focused) pulses that have a near-uniform "top hat" profile, or particularly a super-Gaussian irradiance profile, in proximity to an aperture mask 68 downstream of optical element 64. Such beam shaping components may include aspheric optics or diffractive optics. In one embodiment, lens 66 comprises imaging optics useful for controlling beam size and divergence. Skilled persons will appreciate that a single imaging lens component or multiple lens components could be employed. Skilled persons will also appreciate, and it is currently preferred, that shaped laser output can be employed without using an aperture mask 68.

[0075] In one embodiment, the beam shaping components include a diffractive optic element (DOE) that can perform complex beam shaping with high efficiency and accuracy. The beam shaping components not only transform the Gaussian irradiance profile to a near-uniform irradiance profile, but they also focus the shaped output to a determinable or specified spot size. Although a single element DOE is preferred, skilled persons will appreciate that the DOE may include multiple separate elements such as the phase plate and transform elements disclosed in U.S. Pat. No. 5,864,430 of Dickey et al., which also discloses techniques for designing DOEs for the purpose of beam shaping. The shaping and imaging techniques discussed above are described in detail in International Publication No. WO 00/73013 published on December 7, 2000. The relevant portions of the disclosure of corresponding U.S. Patent Application No. 09/580,396 of Dunsky et al., filed May 26, 2000 are herein incorporated by reference.

[0076] Employing a clipped or imaged shaped Gaussian beam may facilitate better singulation in a multi-step process. In addition to facilitating greater spot shape control and consistency and depth control (particularly for imaged shaped), beam spots with minimized tails generate redep debris that are more easily cleaned by nonaggressive cleaning techniques than redep debris generated by unmodified Gaussian beam spots. Furthermore, the uniform irradiance profile facilitates the ability to stop more precisely upon a lower layer or on the substrate material without causing damage, and also thereby enhances the selectivity of a notch cut of a film over an underlying substrate or another underlying film since there is little or no change in the illuminated intensity across the spot, allowing better selectivity between different materials. Other potential benefits include the ability to more precisely control the sidewall angle of the cut through a layer or the ability to use a larger spot size while achieving uniform irradiance across the spot area.

[0077] The pulse energy used for cutting silicon using preferred focused UV spot sizes is greater than 200 μJ, and preferably greater than 800 μJ, per pulse at pulse repetition frequencies greater than 5 kHz and preferably above 10 kHz. An exemplary setting provides 9.1 W at 13 kHz. An exemplary laser pulsewidth measured at the full width half-maximum points is less than 80 ns. Alternative and/or complementary exemplary process windows include, but are not limited to, about 3.5-4.5 W UV at the work surface at about 10 kHz through about 20-30 W UV at 20-30 kHz, such as 15 W at 15 kHz.

[0078] UV laser output 16 is optionally passed through a variety of well-known expansion and/or collimation optics 18, propagated along an optical path 20, and directed by a beam positioning system 30 to impinge laser system output pulse(s) 32 on a desired laser target position 34 on workpiece 12 such as a silicon wafer. An exemplary beam positioning system 30 may include a translation stage positioner that may employ at least two transverse stages 36 and 38 that support, for example, X, Y, and/or Z positioning mirrors 42 and 44 and permit quick movement between target positions 34 on the same or different workpieces 12.

[0079] In an exemplary embodiment, the translation stage positioner is a split-axis system where a Y stage 36, typically moved by linear motors along rails 46, supports and moves workpiece 12, and an X stage 38, typically moved by linear motors along rails 48, supports and moves a fast positioner 50 and associated focusing lens(es) or other optics 58 (FIG. 1). The Z dimension between X stage 38 and Y stage 36 may also be adjustable. The positioning mirrors 42 and 44 align the optical path 20 through any turns between laser 14 and fast positioner 50, which is positioned along the optical path 20. The fast positioner 50 may for

example employ high resolution linear motors or a pair of galvanometer mirrors 60 (FIG. 5) that can effect unique or repetitive processing operations based on provided test or design data. The stages 36 and 38 and positioner 50 can be controlled and moved independently or coordinated to move together in response to panelized or unpanelized data. A split axis positioning system 30 is preferred for use in large area of travel applications, such as cutting 8" and especially 12" wafers.

[0080] Fast positioner 50 may also include a vision system that can be aligned to one or more fiducials on the surface of the workpiece 12. Beam positioning system 30 can employ conventional vision or beam to work alignment systems that work through objective lens 58 or off axis with a separate camera and that are well known to skilled practitioners. In one embodiment, an HRVX vision box employing Freedom Library software in a positioning system 30 sold by Electro Scientific Industries, Inc. is employed to perform alignment between the laser system 10 and the target locations 34 on the workpiece 12. Other suitable alignment systems are commercially available. An exemplary alignment system employs bright-field, on-axis illumination, particularly for specularly reflecting workpieces like lapped or polished wafers, but dark-field illumination or a combination of dark-filed illumination and bright-field illumination may be employed.

[0081] For laser cutting, the beam positioning system 30 is preferably aligned to conventional typical saw cutting or other fiducials or a pattern on wafer surface. If the workpieces 12 are already mechanically notched, alignment to the cut edges is preferred to overcome the saw tolerance and alignment errors. Beam positioning system 30 preferably has alignment accuracy of better than about 3-5 μm, such that the center of the laser spot is within about 3-5 μm of a preferred cutting path, particularly for laser beam spot sizes such as 10-15 μm. For smaller spot sizes, the alignment accuracy may preferably be even better. For larger spot sizes, the accuracy can be less precise. In addition, beam positioning system 30 may also employ an Abbe errors correction system such as described in detail in International Publication No. WO 01/52004 A1 published on July 19, 2001 and U.S. Publication No. 2001-0029674 A1 published on October 18, 2001. The relevant portions of the disclosure of the corresponding U.S. Pat. Appl. No. 09/755,950 of Cutler are herein incorporated by reference.

[0082] Many variations of positioning systems 30 are well known to skilled practitioners and some embodiments of positioning system 30 are described in detail in U.S. Pat. No. 5,751,585 of Cutler et al. The ESI Model 2700 or 5320 micromachining systems available from Electro Scientific Industries, Inc. of Portland, Oregon are exemplary implementations of

positioning system 30. Other exemplary positioning systems such as a Model series numbers 27xx, 43xx, 44xx, or 53xx, manufactured by Electro Scientific Industries, Inc. in Portland, Oregon, can also be employed. Some of these systems which use an X-Y linear motor for moving the workpiece 12 and an X-Y stage for moving the scan lens are cost effective positioning systems for making long straight cuts. Skilled persons will also appreciate that a system with a single X-Y stage for workpiece positioning with a fixed beam position and/or stationary galvanometer for beam positioning may alternatively be employed. Those skilled in the art will recognize that such a system can be programmed to utilize toolpath files that will dynamically position at high speeds the focused UV laser system output pulses 32 to produce a wide variety of useful patterns, which may be either periodic or non-periodic.

[0083] An optional laser power controller 52, such as a half wave plate polarizer, may be positioned along optical path 20. In addition, one or more beam detection devices 54, such as photodiodes, may be downstream of laser power controller 52, such as aligned with a positioning mirror 44 that is adapted to be partly transmissive to the wavelength of laser output 16. Beam detection devices 54 are preferably in communication with beam diagnostic electronics that convey signals to modify the effects of laser power controller 52.

[0084] Laser 14 and/or its Q-switch, beam positioning system 30 and/or its stages 36 and 38, fast positioner 50, the vision system, any error correction system, the beam detection devices 54, and/or the laser power controller 52 may be directly or indirectly coordinated and controlled by laser controller 70.

[0085] Laser system 10 may employ two or more laser heads of the same or different types (with the same or different wavelengths and/or other parameters) that emit respective laser outputs 16 that propagate along shared portions of optical path 20, such as with the aid of wave plates, polarizers, and/or combiners, or along completely independent optical paths 20 to impinge substantially identical positions on workpiece 12. Skilled persons will appreciate that such lasers 14 may be mounted side by side or one on top of the other and both attached to one of the translation stages 36 or 38, or the lasers 14 can also be mounted on separate independently mobile heads. The firing of such lasers 14 could be coordinated by laser controller 70. Such a laser system could produce a combined laser output 32 impinging on the work surface having an increased energy per pulse that could be difficult to produce from a conventional single laser head. Such an increased energy per pulse can be particularly advantageous for ablating deep trenches, or slicing or dicing through thick silicon wafers or other workpieces 12. U.S. Pat. Appl. No. 10/017,497 ('497 Application) of Baird

et al. describes such a multiple head laser system and more generally describes using ultraviolet laser ablation to directly and rapidly form patterns with feature sizes of less than 50 μm in hard to cut materials, such as silicon. U.S. Pat. Appl. No. 10/017,497 of Baird et al. is herein incorporated by reference.

[0086] For the purpose of providing increased flexibility in the dynamic range of energy per pulse, a fast response amplitude control mechanism, such as an acousto-optic modulator or electro-optic modulator may be employed to modulate the pulse energy of successive pulses. Alternatively, or in combination with the fast response amplitude control mechanism, the pulse repetition frequency may be increased or decreased to effect a change in the pulse energy of successive pulses. FIG. 4 displays the characteristic relationship between pulse energy and pulse repetition frequency (PRF) of a laser 14 employed during practice of the invention. As FIG. 4 indicates, pulse energies of greater than 200 μJ can be obtained from the Model 210-V06. In addition, the characteristic relationship between pulse energy and PRF for alternative lasers, Lightwave Electronics 210-V09L and Lightwave Electronics 210-V09H, are also shown. Those skilled in the art will appreciate that FIG. 4 is illustrative of the principal described and alternate embodiments of laser system 10 will produce different characteristic relationships between pulse energy and pulse repetition frequency. Skilled persons will appreciate that FIG. 4 presents one example only and that the E vs. PRF curve can be very different for different laser mediums.

[0087] FIG. 5 depicts a simplified monitoring system 80 that employs one or more sensors 82 optically in communication with the target location 34 on the workpiece 12. In one embodiment, a mirror 84 is positioned along the optical path 20, upstream or downstream of fast positioner 50, and is transmissive to the outgoing beam but reflects any incoming radiation to the sensors 82. Skilled persons will appreciate, however, that mirrors and other optics associated with monitoring system 80 may be aligned completely independently from optical path 20 and a variety of detection techniques can be employed. The sensors 82 of monitoring system 80 may be sensitive to the intensity, albedo, wavelength and/or other properties of light emitted, scattered, or reflected from the target material or support material positioned beneath it. Sensors 82 may, for example, be photodiodes and may include or form part of beam detection devices 54. Typically, sensors 82 detect less feed back when the cutting path 112 is open. Sensors 82 may, for example, communicate with laser controller 70 and/or beam positioning system 30 to provide the cut status information continuously or for one or more discrete points along a given segment 122 (FIG. 17). By employing real time

monitoring of the completed and uncompleted portions or areas of the cutting path 112, the laser system 10 through a beam positioning system 30 can direct the laser system output 32 only to portions of the cutting path 112 that need additional cutting. This monitoring and selective segment processing reduce the amount of time spent along a traditional cutting path 112 impinging already completed portions along the entire path. Thus, cutting throughput is improved.

[0088] FIG. 6 depicts a cutting path 112 having respective first and second transverse directions 92 and 94. Laser system 10 optionally employs a polarization tracking system 90 (FIG. 2) that includes a polarization control device, such as a rotatable half wave-plate or a Pockel's cell, to change the polarization direction or orientation of laser system output 32 to track changes in the cutting path direction. The polarization control device may be positioned upstream or downstream of fast positioner. When laser system output 32 is in a trench and moving relative to the target material, the laser system output 32 impinges the target material at a nonnormal angle, resulting in a polarization effect that is not present when impingement is nonmoving and normal to the target material. Applicants have noted that coupling efficiency and therefore throughput are increased when the polarization direction is in a particular orientation with respect to the cutting direction. Therefore, the polarization tracking system 90 may be employed to keep the polarization orientation in an orientation that maximizes throughput. In one embodiment, polarization tracking system 90 is implemented to keep the polarization orientation parallel with the cutting direction or orientation to increase the coupling energy of the laser system output into the target material. In one example, when cutting directions 92 and 94 differ by an angle theta, the half waveplate is rotated by theta/2 to change a first polarization orientation 96 to a second polarization orientation 98 to match the cutting direction change of theta.

[0089] The polarization control device may also be implemented as a variable optical retarder, such as a Pockel's cell. A drive circuit conditions a polarization state control signal, which the drive circuit receives from a processor associated with beam positioning system 30 and/or laser controller 70. In this example, there is a one-to-one correspondence between the magnitude of the polarization state control signal and a beam positioning signal such that the polarization direction of the light beam is maintained generally parallel to its cutting path. U.S. Pat. No. 5,057,664 of Johnson et al. describes a method for correlating the direction of beam polarization with trimming direction. Skilled persons will appreciate that the optimized polarization orientation versus cutting direction may vary with laser systems and materials, such that the preferred polarization orientation may be parallel, vertical, orthogonal, elliptical

(with the long axis in any given orientation), or any other orientation with respect the laser pass or cutting direction.

[0090] FIG. 7 is a representative illustration of a chuck assembly 100 on which silicon workpieces 12 are preferably placed for throughcut processing using an ultraviolet segment cutting method. Chuck assembly 100 preferably includes a vacuum chuck base 102, a chuck top 104, and an optional retaining carrier 106 placed over chuck top 104 for the purpose of supporting a silicon workpiece 12 and retaining it after a throughcut application. Base 102 is preferably made from traditional metal material and is preferably bolted to an additional plate 108 (FIG. 2). Plate 108 is adapted to be easily connected to and disengaged from at least one of the stages 36 or 38. The engagement mechanism is preferably mechanical and may include opposing grooves and ridges and may include a locking mechanism. Skilled person will appreciate that numerous exact alignment and lock and key mechanisms are possible. Skilled persons will also appreciate that the base 102 may alternatively be adapted to be secured directly to the stages 36 or 38.

[0091] Chuck top 104 and optional retaining carrier 106 may be fabricated from a material that has low reflectivity (is relatively absorbent or relatively transparent) at the ultraviolet wavelength selected for the particular patterning application to minimize backside damage to silicon workpieces 12 around through trenches from reflective energy coming off the metal chuck top after through processing has been completed. In one embodiment, chuck top 104 or retaining carrier 106 may be fabricated from an ultraviolet absorbing material, such as Al or Cu, in order that laser system 10 may use a tool path file of the pattern of shallow cavities to be drilled into the workpiece 12 to cut the corresponding pattern into the material of chuck top 104 and/or retaining carrier 106. The cavities may, for example, correspond to intended throughcuts and prevent backside damage to the workpiece 12 during throughcut operations. In addition, any debris from the process may settle into the cavities away from the backside of workpiece 12. In one preferred embodiment, the pattern of the shallow cavities is processed to have dimensions slightly larger than those of the corresponding workpieces 12 after processing, thereby enabling processed workpieces 12 to settle into the cavities of the retaining carrier 106. A retaining carrier 106 with cavities or through holes may be very thick to increase the distance between chuck top 104 and the focal plane. Retaining carrier 106 may also be machined to contain shallow cavities into which the processed silicon workpieces 12 settle after through processing operations. In an alternative embodiment, where 355 nm output is employed, a UV-transparent chuck top 104 may be fabricated from ultraviolet-grade or excimer grade fused silica, MgF_2, or CaF_2. In another

embodiment, UV-transparent chuck top 104 may alternatively or additionally be liquid-cooled to assist in maintaining the temperature stability of the silicon workpieces 12. More details concerning exemplary chuck assemblies 100 can be found in the '497 Application of Baird et al.

[0092] FIG. 8 is a simplified plan view of an enlarged workpiece 12 sequentially impinged by slightly overlapping spots having a spot area of diameter, d_{spot}, along a trim line or cutting path 112. With reference to FIG. 8, although the spot area and d_{spot} generally refer to the area within the outside edge of the laser spot when the laser power falls to $1/e^2$ of the laser peak power, these terms are occasionally used to refer to the spot area or diameter of the hole created by a single pulse or the width of a kerf created in a single pass of pulses. The difference between the $1/e^2$ dimension and the kerf diameter will vary with the laser, the material, and other parameters.

[0093] The distance of new target material impinged by each sequential laser pulse is called the bite size d_{bite}. A preferred bite size d_{bite} for laser cutting of many materials of interest, such as silicon, includes an advantageous bite size range of about 0.5 μm to about d_{spot}, and more preferably a range of about 1-50 μm, with a typical range of about 1-5.5 μm, and most typically a bite size of about 1 μm. For some materials, adjusting the bite size results in a condition where the redep debris generated may be easier to remove. The bite size can be adjusted by controlling the speed(s) of the laser beam positioning system 30 and coordinating the movement speed(s) with the repetition rate of the firing of the laser 14.

[0094] FIGS. 9A-9E show simplified side sectional views of a generic workpiece 12 as it undergoes sequential processing steps 28 of an exemplary laser cutting or drilling process. In one embodiment, separate processing steps 28a-28d are used in succession to cut through an optional sacrificial layer 22 and films or device layers 24a and 24b and substrate 26 from the top layer 24 down through the substrate 26.

[0095] With reference to FIG. 9, the top layer could either be a device layer 24a, or could be an optional sacrificial protection layer 22 to protect important features, such as solder bumps on die or features on die, such as laser diodes, optical waveguides, or MEMS components, etc., from redep and/or to facilitate cleaning of nonpermanent redep. A preferred sacrificial layer comprises a conventional lithographic photoresist or a laser ablatable resist. Unfortunately, as previously discussed, conventional materials used for sacrificial layer 22 have a tendency to burn when impinged by laser output suitable for dicing or removal of many types of device layer 24. It may be desirable to remove about a 1-25 μm

(typically 2-7 μm) wider area of the sacrificial layer 22 in proximity to the prospective edges 40 of the cuts to be made in the underlying layers 24 to create a small uncovered zone 56 on each side of the intended cut. The sacrificial layer 22 is preferably removed by a distinct processing step 28a, although some applications might combine the removal of sacrificial layer 22 with the removal of one or more of the device layers 24. The sacrificial layer 22 can be removed by conventional lithographic techniques, or by direct ablation or expose and etch solid-state UV laser techniques disclosed in U.S. Pat. No. 6,025,256 of Swenson et al. An example of parameters for resist-processing laser system output 32 includes a beam positioning offset of 10-20 μm from a prospective edge 40, a 7 μm bite size, at 14 kHz at 30 μJ at 266 nm. If direct laser ablation is performed, the laser output parameters, particularly the power density, are adapted to be insufficient to adversely affect the underlying device layers 24 or substrate 26. In an exemplary embodiment, the same laser 14 that is used to process device layers 24 is used to remove the strip of sacrificial layer 22, but the laser system output 32 is generated at a higher repetition rate or the laser spot may be defocused to reduce the power density. If appropriate for a specific layout of rows or dies, a larger spot size or multiple adjacent or partly overlapping cutting paths 112 of laser system output 32 can be employed for any of the laser processing steps 28. The later process may be desirable to eliminate or prevent formation of a lip along one side of the resulting cut. Details concerning a desirable amount of overlap for some applications can be found in U.S. Pat. No. 6,255,621 of Lundquist et al.

[0096] With reference to FIGS. 9B and 9C, processing steps 28b and 28c may be distinct with their own separate sets of processing parameters and may be performed by the same or separate lasers 14, or these device layer processing steps 28 may be performed as a single step at a single set of parameters by a single laser 14, for example. The parameter set may therefore be tailored to each particular device layer 24 or to a single process that can facilitate removal of two or more device layers 24. With reference to FIG. 9D, processing step 28d is preferably distinct from any of the prior processing steps 28, although some applications that process one or more device layers 24 along with substrate 26 with the same process technique may yield advantages, particularly for throughput. Processing step 28d can be a laser process in some applications or can be a non-laser technique, such as mechanical saw cutting, in other applications. Exemplary laser techniques for cutting substrates 26 are describe later in detail. Saw cutting techniques are well known to skilled practitioners. .An advantage of mechanical saw cutting is that it offers high throughput and suits the established infrastructure in the industry.

[0097] FIG. 9E shows workpiece 12 after it has been throughcut by processing steps 28. Skilled persons will appreciate that the cuts shown may either be a dicing cut or a drilled via. If desirable, based on the particular application and the nature of the layer materials, processing steps 28 may be employed to make successively smaller cut widths to reduce or eliminate any undesirable effects of successive processes on the previous layers 24. For many applications, however, it may be preferable to cleared open all layers 24 and substrate 26 to about the same width. If desirable, further process steps may occur where a laser 14, for example, is used to clean up the edges 40 of the cuts made in the earlier steps 28. Skilled persons will also appreciate that both sides of a workpiece 12 may support layers 24 and that processing steps 28 may be applied to each side simultaneously or sequentially.

[0098] One skilled in the art will realize that, although a DPSS UV laser is preferred for many applications, an excimer laser at an appropriate UV wavelength can be used with appropriate-sized line-making masks (about the width of preferred Gaussian spot sizes) for the above-described laser cutting operations for those layers UV ablation is preferred. The line-making masks can have a length the size of an entire column of dies or as little as the desired edge length of each die. Skilled persons will appreciate that if the semiconductor industry moves toward making die on different types of wafers, like InP, sapphire, SOS, SOI, etc., the processes disclosed herein can be applied to devices manufactured with or on such wafers. Silicon carbide and titanium carbide, or other insulating (non-semiconductor) substrates, may also be similarly processed.

[0099] FIGS.10A-10H (collectively FIG. 10) show simplified side sectional views of a generic workpiece as it undergoes process steps of an exemplary laser rounding process. In one example, rows or dies, such as individual sliders, are separated along dicing streets to form corners 72 on edges 40 in accordance with processing steps 28. The respective edges 40 can then be rounded with laser system output 32. With reference to FIG. 10A, an optional sacrificial protection layer 22 may be applied to a device layer 24, such as a patterned air-bearing surface (ABS) all of the surfaces of the workpiece 12 prior to laser rounding to protect device features such as rails 76 or pole tips, from redep and/or to facilitate cleaning of nonpermanent redep.

[00100] With reference to FIGS. 10B and 10C, it is preferable to remove about a 10-25 μm wide area of sacrificial layer 22 from covering the ABS in proximity to prospective corners 72 to create a small uncovered zone 56. Uncovered zone 56 is preferably wider than the spot area of laser system output 32a but narrow enough so that all device features remain covered.

These strips of sacrificial layer 22 can be removed as previously discussed. In a preferred embodiment, the same laser 14 that is used to round corners 72 is used to remove the strip of sacrificial layer 22, but the laser system output 32a is generated at a higher repetition rate or the laser spot may be defocused to reduce the power density. FIG. 10C shows uncovered zone 56 after a strip of sacrificial layer 22 has been removed.

[00101] With reference to FIG. 10D, laser system output 32b is applied to layer 22 in uncovered zone 56. Laser output 32b is preferably positioned perpendicular to the layer 22, with the spot centered at corner 72, as shown; however, skilled persons will appreciate that other impingement angles and offsets from corners 72 can be employed. Although a single laser pass 132 is preferable, multiple passes 132 of laser system output 32 can be employed. FIG. 10E shows redep 74a on the surface of sacrificial layer 22 and redep 74b on the surface of rounded corner 78, collectively redep 74, that may result from application of laser system output 32.

[00102] After the laser rounding operation shown in FIG. 10D, a cleaning operation shown in FIG. 10F can be used to remove any laser-generated debris 74 that may have accumulated in the uncovered zone 56. A major advantage of employing a sacrificial layer 22 is that it permits the use of more aggressive cleaning techniques, such as ion milling or reactive ion etching (RIE), to remove redep 74b without risk of damage to device layers 24. These aggressive cleaning techniques may also remove a surface portion of sacrificial layer 22 and any redep 74a thereon. Without sacrificial layer 22, less aggressive cleaning techniques, such as solvent or surfactant applications with or without ultrasound or mechanical scrubbing, are preferred. FIG. 10G shows workpiece 12 after cleaning. Finally, sacrificial layer 22 is stripped off the entire workpiece 12, removing any remaining laser-generated debris 74a with it. FIG. 10H shows an uncovered workpiece 12, such as a die or slider, with its corner rounded. These same cleaning techniques may be employed after process steps 28 if no corner rounding or edge treatments are desired.

[00103] FIGS. 11A-11F (collectively FIG. 11) show simplified side sectional views of a generic workpiece 12 as it undergoes process steps of an exemplary laser cutting process (row slicing or die dicing). With reference to FIG. 11A, an optional sacrificial protection layer 22 may be applied to device layer 24 or all of the workpiece surfaces, as previously described, prior to laser cutting. With respect to the overall process of manufacturing dies, in one example, sacrificial layer 22 is applied directly after an ABS has been patterned and before the photoresist mask has been removed. Alternatively, the rounding and/or severing

processes can be performed using a mask before or after patterning. It can also alternatively be applied after the mask has been removed or after the dies have been singulated. Instead of, or in addition to, covering the surface with sacrificial layer 22, laser cutting may be performed from the back side of workpiece 12 so that laser-generated debris 74 becomes irrelevant.

[00104] With reference to FIGS. 11B and 11C, preferably a 10-50 μm wide area of sacrificial layer 22 covering layers 24 in proximity to intended edges 40 is removed to create an uncovered zone 56. These strips of sacrificial layer 22 can be removed as previously described. FIG. 11C shows uncovered zone 56 receiving processing step 28b after the strip of sacrificial layer 22 has been removed.

[00105] With reference to FIG. 11D, processing step 28d is applied to substrate. Laser output 32 is preferably positioned perpendicular to the substrate 26, with the spot centered between intended edges 40, as shown; however, skilled persons will appreciate that other impingement angles and offsets from intended edges 40 can be employed. Multiple passes 132 of laser output 32 are typically employed for both row slicing and slider dicing, and can be applied in traditional full length scans or segmented scans as later discussed. Laser output 32 used for laser cutting may employ a higher peak power density than laser output 32 used for laser rounding.

[00106] With respect to a particular example for slider dicing, although using common parameters for slicing through both the alumina and the AlTiC is advantageous for simplification, it may be desirable for throughput, for example, to employ different parameters for alumina slicing output 32 to slice through the alumina than for AlTiC slicing output 32 to slice through AlTiC. In particular, it may be desirable to use 266 nm or 355 nm to cut the alumina and 355 nm or 532 nm to cut the AlTiC. In one embodiment, row slicing through the alumina on multiple rows is performed with one output 32 and then slicing through the AlTiC is performed in the notches with another output 32 to finish the cuts. Alternatively, a row may be sliced completely through with sequential differents outputs 32 before a second row is sliced. Each of the two different laser outputs 32 maybe applied in a single or in multiple passes, along single or adjacent cutting paths 112, and/or in full length scans or segmetned scans. Switching the parameters of output 32 can be achieved with a single laser employing a switchable wavelength, repetition rate, or focus depth, or can be achieved through a multi laser head system, with different laser heads responsible for the different laser outputs 32. With respect to slider dicing, each traverse throughcut cut 150

traverses regions of sliders that are completely alumina and regions that are completely AlTiC. Accordingly, one output 32 can be applied in one or more passes along the alumina portions of cuts 196 and then another output 32 can be applied in one or more passes along the AlTiC portions of cuts 196. Alternatively, each cut 196 can be made completely one at a time, switching between alumina processing output 32 and AlTiC processing output 32 for each pass.

[00107] FIG. 11E shows separated edges 40 with redep 74a on the surface of sacrificial layers 22 and redep 74b on the surface of edges 40. FIG. 11F shows the beginning of the laser rounding process, described in connection with FIG. 10, that is applied to both corners 72. The debris 74 can optionally be cleaned off before the laser rounding process is performed to provide a flatter surface to facilitate rounding the edges to a preferred radius of curvature of about 20-25 μm Although laser cutting without the additional laser rounding step will provide benefits over mechanical cutting, performing a laser rounding step in addition to laser cutting is preferred.

[00108] Applying one or more additional laser processing passes 132 along the newly formed corners 72 can change the radius of curvature along the corners 72. Furthermore, a more gradual slope can be obtained by employing one or a small number of passes slightly interior of an edge and gradually increasing the number of passes as the beam is positioned more closely to the edge. FIG.12 shows a symbolic representation of forming such a gradually sloped edge 200 with the number of arrows in each column representing the number of passes. It is noted that an increased radius of curvature can also be achieved by performing one or multiple passes directly centered at the edge. Generally, the slope or angle of the edge or sidewall can be controlled by controlling the spacing of the lines of laser spots as well as the distances from the edge and number of passes. More passes at or near the edge results in a steeper angle, and passes further from the edge can be used to produce a shallower slope.

[00109] Although laser sacrificial layer strip removal, laser cutting, and laser rounding may entail multiple laser process steps at different parameters, an all laser process has many advantages and employs repositioning along only a single axis for each linear operation.

[00110] Laser cutting also destroys significantly less material (kerfs of less than 50 μm wide and preferably less than 25 μm wide) than does mechanical cutting (slicing lanes of about 300 μm and dicing paths of about 150 μm) so that sliders or other devices or dies can be manufactured much closer together, allowing many more devices to be produced on each

workpiece 12. Thus, the laser cutting process minimizes the pitch between rows 86 and the pitch between dies. In an example, the pitch between rows 86 can be 350 μm and the pitch between dies such as sliders can be 1025 μm, realizing about a 33% increase in the number of rows 86 and a gain of about one slider for every thirteen sliders per row 86. Skilled persons will appreciate that these exemplary numbers are provided in connection with a slider disk head example and may be very different for different types of dies or devices.

[00111] Elimination of the mechanical cutting can also simplify manufacture of devices or dies. In particular, mechanical cutting can impart significant mechanical stress to the dies such that they come off carrier 106. To avoid losing rows 86, slider manufacturers, for example, typically employ strong adhesives or epoxies between rows 86 and carrier 106. An all laser process significantly reduces the mechanical strength requirements of the adhesive used for fixturing rows 86 onto carrier 106. Laser rounding and/or cutting, therefore, permits the elimination of strong adhesives or epoxies used to affix rows 86 to carrier 106 and the harsh chemicals needed to remove them. Instead, the adhesives can be selected for ease of debonding, such as the reduction of debond time and less exposure to potentially corrosive chemicals, and for amenability to UV laser processing, greatly reducing risk of damage to dies, particularly device layers 24, and thereby enhancing yield.

[00112] Laser row slicing reduces row bow because laser slicing does not exert as much mechanical stress as mechanical slicing. However, if row bow or other of the row defects are apparent, the rows 86 can be laser diced (and re-sliced) to compensate for these defects without concern for the critical die to die alignment needed between rows 86 for mechanical dicing of sliders, for example.

[00113] FIG. 13 demonstrates an exemplary laser process for row defect compensation. Because positioning system 30 can align to edges 40, device features, and or fiducials, laser system 10 can process each row 86 and/or each die, such as sliders, independently. With respect to slanted row 86b, the laser spot can perform traverse cuts 196 across row 86b at appropriate positions with respect to outer rails 76 with stage and/or beam translations 198 between each cut 196 to effect a square (or rectangular) wave pattern or to generally make cuts 196 at angles such that the surfaces of sliders or dies are substantially perpendicular to each other. Numerous other cutting patterns are possible such as making all cuts in a first column before making all cuts in second column. Sliders or dies in rows 86a and 86c can be singulated in a similar fashion regardless of angle or offset. With respect to row 86d, the rectangular wave cut and translate pattern can be curved to align with the row bow. Thus, so

long as the mask pattern for device features is properly aligned to pole tips, for example,, laser dicing can compensate for row fixturing defects and perhaps save entire rows 86 of sliders or dies that would be ruined by mechanical dicing. Skilled persons will appreciate that the spacing between sliders or dies in FIG. 13 is significantly smaller than permitted by prior art mechanical dicing.

[00114] FIG. 14 shows a flow diagram of a simplified cutting and rounding process with simplified side sectional views of a generic workpiece 12 as it undergoes process steps 28. In this alternative embodiment, a process step 28d employs mechanical cutting blade or laser output 32 notches rows 86 or individual dies along cutting streets to a depth, preferably above an adhesive layer if a combination of laser and mechanical notching or cutting is to be employed. Alternatively, for preslice notching, laser output 32 may be employed to notch all the way through the alumina material. FIG. 14b shows the result of laser notching with a solid line and shows the result of mechanical notching with a broken line. Laser output 32 then rounds the desired edges and/or corners, and finally the same or differetnt processing step 28d is reapplied with mechanical cutting blade or laser output 32 to finish the separation of rows 86 or singulation of the dies. The width of the kerf or diameter used for the cutting process can be less than or equal to the width of the kerf or diameter used for the notching process. A sacrificial layer 22 and the related steps associated with it may be employed prior to a notching process. Skilled persons will appreciate that edges on the bottom side can optionally be done by this notching technique, preferably such that top and bottom alignment is conserved. Such notching would greatly facilitate subsequent laser separation of the rows 86 or dies. One advantage of this technique is that there are fewer pieces to align since the parts are still referenced to each other, i.e., the rounding is completed before the pieces are separated. Another advantage is that the preliminary notch does not expose the adhesive layer where mechanical cutting is to be employed, since the adhesives needed to withstand mechanical cutting are particularly volatile in response to laser radiation.

[00115] FIG.15 shows a flow diagram of an alternative cutting and rounding process with simplified side sectional views of a generic workpiece 12 as it undergoes process steps. With reference to FIG. 15, processing step 28e using rounding laser output 32 is applied along two parallel trim lines. The trim lines are spaced such that the prospective edges 40 align with the centers of the trenches 202 produced by processing step 28e. In FIG.15b, a dice blade or laser 14 cuts the workpiece surface between the trenches 202 to produced rounded separate parts shown in FIG.15c. In this example, processing step 28e is applied after processing steps 28a-28c but before processing step 28d. In an alternative example, processing steps 28e may

be applied before or substituted for one or all of processing steps 28a-28c as demonstrated in FIG. 15d.

[00116] FIG. 15d also demonstrates that processing steps 28e do not have to be aligned to the prospective edges 40 and can be applied at a distance from the prospective edges 40.

[00117] In this embodiment, the geometry of a layer 24 or layers 24 may be modified by one or several laser processes such that the subsequent cutting or drilling of the substrate does not cause damage in the active area of the devices. For example, a process sequence may include an initial notching of layer 24 or layers 24 on either side of the cut without removing all the material from the dice lane area such that the outermost edges formed by the laser trenches are unaffected by the subsequent substrate dicing process. As discussed above, this laser notching can be performed using parameters specifically optimized for cutting the layers 24 cleanly without inducing damage that would occur if substrate dicing parameters were used. Use of this geometry modification would include, but is not limited to, the formation of trenches or other shapes outside the dicing kerf which would act as crack stops or mechanisms for arresting delamination which may be induced by the wafer substrate dicing step.

[00118] FIG. 16 shows an alternative rounding, notching, and separating process. In FIG. 16a, multiple adjacent or partly overlapping passes 132 (as previously described) of laser output 32 or a large spot size pass (as previously described) are used to create an extra wide notch (FIG. 16b) with rounded edges. Then processing step 28d using a laser 14 or a cutting blade is applied to separate the rows 86 or the dies. This process creates a shelf-like edge shown in FIG. 16c. The edges of the lower shelves can be rounded with processes previously discussed. If steeper edges are desired in the upper notch, then higher intensity pulses or other parameters may be employed for the outermost laser outputs.

[00119] With reference to FIGS. 9-16, it may be desirable to notch through one side of the workpiece 12, preferably about one half the thickness of the workpiece 12, and then finish the row or die separation from the opposite side, preferably by flipping the workpiece 12 and using alignment techniques that are later described. This embodiment may provide significant throughput advantages particularly for high-aspect ratio kerfs. The rounding process can be performed before or after notching or after row or slider separation.

[00120] The above-described performance characteristics of UV laser system 10 can be used for high-speed cutting of semiconductors, and particularly silicon. Such cutting operations may include, but are not limited to, formation or trepanning of large diameter vias

through or partially through silicon wafers or other silicon workpieces 12; formation of through or partly through trenches of complex geometry for the purpose of singulation of processed die on silicon wafers or silicon workpieces 12; formation of microtab features to separate microcircuits formed in silicon from parent wafers; formation of features on and/or singulation of AWGs and sliders; and formation of features in MEMS. In addition, the present invention facilitates feature formation without significant melt lip formation, without significant slag formation, and without significant peel back of the feature edge.

[00121] Applicants have discovered that laser cut rates for silicon, and other like materials, can be significantly improved by segment scanning or cutting instead of traditional methods of full path cutting. The processing throughput can be enhanced by appropriate selection of segment length, segment overlap, and/or overlap of subsequent passes within each segment, as well as by selection of other processing parameters.

[00122] By segment cutting, the consequences of material backfill in the cut trench may be avoided or minimized. Trench backfill may be a significant limitation to dicing speed. It is proposed that by making quick short open segments or subsegments, the laser system 10 can provide an avenue for much of the laser ejected material to escape rather than refill the trenches as they are being cut. Hence, reduced trench backfill will decrease the number of passes necessary to cut through a given portion of the cutting path 112. FIGS. 17-23 present exemplary segmented cutting profiles 110a-110f (generically profiles 110) employed in the present invention. The techniques presented below generally permit a 750 μm-thick silicon wafer to be cut with only about 4 W UV laser power at 10 kHz in about 26 or fewer passes compared to the 150 passes needed using a conventional laser cutting profile.

[00123] FIG. 17 depicts a simplified representation of an exemplary segmented cutting profile 110a of the present invention. With reference to FIG. 17, cutting profile 110a is shown, for convenience, having a path cutting direction (indicated by the direction of the arrow) from left to right along cutting path 112 and having generally distinct cutting segments 122a, 122b, and 122c (generally, cutting segments 122) formed in a segment cutting direction (or laser pass direction) that is the same as the path cutting direction by respective groups of passes 132a, 132b, and 132c (generically, laser passes 132) of laser system output 32. In this example, the lengths of the laser passes 132 substantially equal the lengths 126 of the segments 122. Skilled persons will appreciate that cutting profile 110a, and subsequent exemplary cutting profiles 110, may preferably include from two to an

infinite number of cutting segments 122, depending on total respective lengths 124 of cutting profiles 110.

[00124] With reference again to FIG. 17, generally a preferred length 126 for cutting segments 122 may be dependent on the characteristics of the material being processed, its thickness, and the response time of the positioning system 30, including its acceleration/deceleration limits, degree of ringing of the mechanical components, and return movement time. For example, if segments are too short, the number of segments for a given cut will be very large, and the amount of time lost to change of direction between passes will be very large. Thus, positioning system characteristics may impact determination of the minimum segment length. Segment length 126 may be a function of bite size, repetition rate, and positioning system performance as well as other possible factors, and each or all of these factors may be optimized based on laser pulse intensity. Skilled persons will appreciate that segments 122a-122c need not have the same lengths 126.

[00125] Generally each segment 122 is scanned substantially collinearly with consecutive passes 132 of laser output 32 (skipping over completely processed portions) until it is completely processed, e.g. a throughcut is made along the entire length 126 of the segment 122 or until the target material is trenched to a desired depth before a subsequent segment 122 is processed. If snapstrates are desired, a series of discontinuous throughcuts may be desirable, or no through hole cutting may be desirable and nearly thorughcut trenches may be desirable. One to several scans across the entire cutting path length can be optionally employed in the process, particularly before and/or after the segment cutting steps, to maximize the throughput and/or improve the cut quality Typically, a through hole can be made in each segment in from 5-10 laser passes such that some of the debris can escape through the through holes. However, if desired, each segment 122 can be processed with multiple passes to an intermediate depth, and the cutting profile can be reapplied, perhaps even in the opposite direction if desirable. If segments are initially processed only to a status where they each have a through hole in one portion, then it may also be advantageous in some circumstances to implement a traditional cutting profile as soon as all the segments 122 include significant through holes. To distinguish from laser punching, skilled persons will appreciate that the segment length 126 is greater than d_{spot}. Furthermore, laser punching each spot to create a through hole before moving along the cutting path 112 would take longer, possibly damage the target material, and cause other less favorable results.

[00126] In an exemplary embodiment, for cutting thick silicon, each segment 122 has a segment length 126 of about 10 μm to 1 mm, typically from about 100 μm to 800 μm, and most preferably from about 200 μm to 800 μm. With respect to cutting profile 110a, segments 122 are preferably slightly overlapped by an overlap distance 136 that may be as small as the bite size or larger than several spot sizes. However, skilled persons will appreciate that the final pass processing segment 122a and the first pass processing segment 122b may be combined into a double length segment 122 (without overlap). Although it is preferred to maintain the same laser parameters during any given pass 132 along a segment 122, skilled persons will appreciate that it is possible to change laser parameters during any given pass to accommodate specific applications.

[00127] FIG. 18 depicts a simplified representation of an exemplary segmented cutting profile 110b. With reference to FIG. 18, cutting profile 110b is shown, for convenience, having a path cutting direction from left to right and having distinct cutting segments 122d, 122e, and 122f (generally, cutting segments 122) formed from respective laser passes 132d, 132e, and 132f in a segment cutting direction that is opposite the path cutting direction. Thus, segment 122d is processed from right to left and then segment 122e is processed from right to left, etc.

[00128] An advantage of cutting profile 110b over cutting profile 110a is that the debris generated while cutting segment 122d is generally scattered in the direction of segment 122e (backwards with respect to the laser pass direction) where there is no preexisting trench to be backfilled by the debris. Any such debris that does land along the subsequent segment 122 to be cut will be immediately processed. In addition, since the path cutting direction is opposite the segment cutting direction, the debris generated will generally not occlude the trench of the previously cut segment 122. Skilled persons will appreciate that other than the difference between path cutting direction and segment cutting direction, most of the discussion concerning FIG. 17 is germane to FIG. 18.

[00129] FIG. 19 depicts a simplified representation of an exemplary segmented cutting profile 110c. With reference to FIG. 19, cutting profile 110c is shown, for convenience, having a path cutting direction from left to right and having distinct cutting segments 122g, 122h, and 122i (generally, cutting segments 122) formed from respective laser passes 132g, 132h, and 132i that each proceed from left to right and from right to left in a back and forth overlapping scanning fashion. In particular, segment 122h is first processed from left to right and then from right to left, etc. until it is completely processed, for example, and then

segment 122i is similarly processed. Because the segments 122 are being processed in both directions, the nonprocessing movement returns of the positioning system 30 is eliminated, resulting in a higher usage of the system capability. Because a laser pass 132 may take longer than nonprocessing movement returns of the positioning system 30, segments 122 in FIG. 19 may be shorter than those used in FIGS. 17 and 18 in applications where it is desirable to impinge debris or exposed portions of a trench within a prescribed period of time from the previous impingement. Other than some of the details specified above, most of the discussion concerning FIGS. 17 and 18 is germane to the example in FIG. 19.

[00130] FIG. 20 depicts a simplified representation of an exemplary segmented cutting profile 110d. With reference to FIG. 20, cutting profile 110d is shown, for convenience, having a path cutting direction from left to right along cutting path 112 and having distinct cutting segments 122j, 122k, and 122m (generally, cutting segments 122) formed from right to left. FIG. 20 also depicts multiple, substantially collinear laser pass sets 140_1, 140_2, and 140_3 (generically laser pass sets 140), each comprising an initial pass 132k and multiple gradually lengthening overlapping and substantially collinear passes 132m-132r, preferably processed in alphabetical order. Although cutting passes $122k_1$-$122r_3$ are depicted as parallel in FIG. 20 for convenience, cutting passes $122k_1$-$122r_3$ are preferably substantially collinear and collinear with the respective segments 122.

[00131] Unlike the slight optional overlaps between adjacent segments 122 associated with the examples in FIGS. 17-19, the overlap lengths associated with adjacent segments 122 or passes 132 in this and the following examples are typically greater than about 10%, more typically greater than about 25%, and most typically greater than about 50%, and occasionally exceeding 67% or 85%. In one particular example where a 300 μm segment is employed, an overlap length of 200 μm is employed; and in another example where a 500 μm segment length is employed, a 250 overlap length is employed.

[00132] One reason to employ laser passes 132 that have different end points within a segment 122 is to prevent a "scan end" effect where more material is stacked at the end of segment 122 whenever it is processed by identical overlapping passes 132. Thus, an advantage of lengthening of consecutive passes 132 or consecutive small groups of passes is to spread the scan effect over longer cut lengths so that the cutting speed across an entire segment 122 or the entire cutting path 112 becomes more uniform, thereby enhancing throughput and cut quality. The scan effect on quality can also be mitigated by employing full cutting path length scans or passes 132 after the segment cutting process is finished.

[00133] Preferably, each pass 132 is employed only once and each laser set 140 is employed only once to process the respective segment 122 to a desired intermediate depth or to a complete through cut before the next segment 122 is processed. Alternatively, laser set 140_1 of cutting passes $122k_1$-$122r_1$ can be repeated until a throughcut is made along some or all of segment 122j, then subsequent laser sets 140 can be repeated segment by segment until the entire cutting path 112 is throughcut. Although only five overlapping passes 132 are shown for each laser pass set 140, skilled persons will appreciate that a substantially greater number of overlapping passes 132 could be employed, particularly with smaller incremental length increases as needed to accommodate the thickness of the target material. Skilled persons will also appreciate that any or all of the passes 132 employed in cutting profile 110d could be processed in both directions instead of a single direction as shown in FIG. 20. Skilled persons will also appreciate that multiple applications of each laser pass set 140 could be employed, that multiple applications of one or more passes 132 in a laser pass set 140 could be employed, that the numbers of each distinct pass 132 within a pass set 140 may differ, and that the number of applications of laser pass sets 140 and laser passes 132 may differ during the processing of a single cutting path 112. Any of these variables may be adjusted in real time in response to monitoring information. Other than the details specified above, much of the discussion concerning FIGS. 17-19 is germane to the example in FIG. 20.

[00134] FIG. 21 depicts a simplified representation of an exemplary segmented cutting profile 110e that is somewhat similar to profile 110d, the cutting segments 122n, 122p, and 122q overlap to a greater degree and the subsequent laser pass sets 140_{2a} and 140_{2b} omit laser passes 132k. With reference to FIG. 21, profile 110e begins with the same laser pass set 140_1 that begins profile 110d. However, laser pass sets 140_{2a} and 140_{2b} omit laser passes 132k and their laser passes 132 increasingly overlap (about 86% in the following example) the previously laser pass set 140. In one example of this embodiment, laser pass $132k_1$, which has a length of 200 μm, is applied 30 times. Then, laser pass $132m_1$, which has a length of 240 μm (200 μm plus 1/5 of the length of pass $132k_1$), is applied 6 times (1/5 of 30 passes). Then, laser pass $132n_1$, which has a length of 280 μm (200 μm plus 2/5 of the length of pass $132k_1$), is applied 6 times. This sequence is continued until laser pass set 140_1 is completed and then performed in connection with laser pass sets 140_{2a} and 140_{2b} with laser passes 132k omitted. In this example, the later portions of each segment 122 may not be throughcut until some of the subsequent segment 122 is processed. An advantage of overlapping the segments 122 to include portions of cutting path 122 that are already throughcut is that any debris created by the shorter laser passes 132 that is deposits on the sides of throughcut

portions is removed by the subsequent longer laser passes 132. The pass sets 140 in this example can exhibit dicing speeds of greater than or equal to 8.5 mm/minute with a 3.5 W UV laser, operated at 10 kHz, on a 750 μm-thick silicon wafer.

[00135] FIG. 22 depicts a simplified representation of an exemplary segmented cutting profile 110f. With reference to FIG. 22, cutting profile 110f is shown, for convenience, having a path cutting direction from left to right and having distinct laser passes $132s_1$-$132t_5$ formed from right to left. Although laser passes $132s_1$-$132t_5$ are depicted as parallel in FIG. 22 for convenience, they are preferably substantially collinear. FIG. 22 depicts an initial laser pass 132s and multiple gradually lengthening overlapping segments$132s_1$-$132t_5$, preferably processed in numerical subscript order. In an exemplary embodiment, the length of laser pass 132s is about 200 μm or 300 μm and the length of each subsequent laser pass 132t is about 500 μm. This exemplary profile can yield dicing speeds of greater than or equal to 10.4 mm/minute with a 3.5 W UV laser, operated at 10 kHz, on a 750 μm-thick silicon wafer. For shallow trenches, each pass 132 may be applied only once, and for throughcuts in thick target materials, each pass may be applied multiple times before the next sequential pass 132 is undertaken. Preferably, each laser pass 132 is applied multiple times to reach a selected intermediate depth before the next laser pass 132 is processed. In one embodiment, each consecutive laser pass 132 receives a single pass of laser output 32 and then the entire profile 110f is repeated or the laser passes 132 are processed in reverse order.

[00136] Although only five overlapping laser passes 132t are shown, skilled persons will appreciate that a substantially greater number of overlapping laser passes 132 could be employed, particularly with smaller incremental length increases as needed to accommodate the thickness of the target material. Skilled persons will also appreciate that any or all of the laser passes 132 employed in cutting profile 110f could be sequentially processed in both directions instead of a single direction as shown in FIG. 22. Other than the details specified above, much of the discussion concerning FIGS. 17-21 is germane to the example in FIG. 22.

[00137] FIG. 23 depicts a simplified representation of an exemplary segmented cutting profile 110g that is somewhat similar to profile 110f. With reference to FIG. 23, odd subscripted laser passes 132_1, 132_3, 132_5, 132_7, and 132_9, have an exemplary pass length of 200 μm and even subscripted laser passes 132_2, 132_4, 132_6, and 132_8 have an exemplary pass length of 270 μm. A group of one of these laser passes 132 is delivered before the next sequential group is delivered. In one example the odd subscripted laser passes 132 are applied more times or to a greater relative depth (60% of cut depth versus 40% of cut depth,

for example) than the even subscripted passes. This cutting profile with the exemplary pass lengths avoids an overlap junction until 5.4 mm along the cutting path 112. Skilled persons will appreciate that a variety of cutting profiles and pass lengths can be employed to reduce scan effects and backfill and thereby facilitate enhanced throughput.

[00138] FIG. 24 is a representative illustration of ultraviolet ablative patterning of a trench or throughcut 150 in a workpiece 12 such as a wafer having an intrinsic silicon substrate 148 of a height or thickness 152 of 750 μm overlaid with a 0.5 μm-thick passivation layer of SiO_2 (not shown). Those skilled in the art will recognize that the thickness of the silicon workpieces and the thickness of the passivation layers will vary.

[00139] The trench 150 is preferably patterned by positioning the silicon workpiece 12 at the focal plane of the laser system 10 and directing a string of successively overlapping laser system output pulses 32 at the silicon workpiece 12 as the laser positioning system 30 moves workpiece 12 along the X- and/or Y-axes of the workpiece 12. The Z-height of the laser focus position can be simultaneously moved coincident with each succeeding laser pass 132 to place the laser focus at a sequentially deeper position in the silicon workpiece 12, thereby maintaining the focused spot at a position more coincident with the remaining silicon surface.

[00140] For forming a trench or throughcut 150 in silicon, an exemplary energy per pulse range is about 100 μJ to 1500 μJ, with a typical a energy per pulse range of about 200 μJ to 1000 μJ and a more typical energy per pulse range of about 400 μJ to 800 μJ, and most preferably an energy per pulse over about 800 μJ is employed. An exemplary PRF range is about 5 kHz to 100 kHz, with a typical PRF range from about 7 kHz to 50 kHz and a more typical PRF range from about 10 kHz to 30 kHz. Those skilled in the art will recognize that the laser performance as shown in FIG. 4 can achieve energy per pulse output at PRFs within the typical ranges described above. An exemplary focused spot size range is about 1 μm to 25 μm, with a typical focused spot size range from about 3 μm to 20 μm and a more typical focused spot size range from about 8 μm to 15 μm. An exemplary bite size range is about 0.1 μm to 10 μm, with a typical a bite size range from about 0.3 μm to 5 μm and a more typical bite size range from about 0.5 μm to 3 μm. The bite size can be adjusted by controlling the speed of either or both of the stages of the laser beam positioning system 30 and coordinating the movement speed(s) with the repetition rate and firing of the laser. An exemplary segment size is about 200 μm to 800 μm. An exemplary combination employing a V06 laser on a 2700 micromachining system used a segment length of 300 μm and a segment overlap of 200 μm provided a very fast dicing speed. Skilled persons will appreciate that for different

applications with different lasers for processing different materials, the preferred laser, segment, pass, and other parameters can be extremely different.

[00141] In one example, a trench or throughcut 150 can be made through 750 μm-thick intrinsic silicon overlaid with a 2.0 μm passivation layer of SiO_2. First the SiO_2 layer 24 is processed at one set of parameters, such as with lower intensity at a high scan speed. Then the silicon substrate 26 is processed using an output pulse energy from the laser 14 of about 360 μJ and using a bite size of 1 μm with a stage velocity of 10 mm/s in fewer than 25 passes over the length of a cutting path 112 over an 8"-diameter workpiece 12 with laser pulses having a focused spot size ($1/e^2$) diameter of 12 μm at the work surface. A trench 150 produced employing parameters described above may, for example, have a top surface opening width (diameter) (d_t) 154 of about 20 μm and an exit width (diameter) (d_b) 156 of about 13 μm, thereby producing an aspect ratio for this trench of about 30:1 and an opening taper angle of 0.4°. In some applications, it may be desirable to create an initial through hole before scanning a segment.

[00142] Persons skilled in the art will further appreciate that the selected segmented profile and segment length and the values of energy per pulse, focused spot size, and number of pulses employed to efficiently produce high quality trenches or throughcuts 150 in silicon may vary according to the material and thickness 152 of the silicon workpiece 12, relative thickness and composition of overlayers, of which SiO_2 is only one example, and the wavelength employed. For example, for production of throughcuts 150 in silicon only 50 μm thick, fewer than ten passes may be employed to produce the desired throughcut.

[00143] Those skilled in the art will recognize that various patterns of varying geometry, including, but not limited to, squares, rectangles, ellipses, spirals, and/or combinations thereof, may be produced through programming of a tool path file used by laser system 10 and positioning system 30 to position silicon workpiece 12 along X and Y-axes during processing. For laser cutting, the beam positioning system 30 is preferably aligned to conventional typical saw cutting or other fiducials or a pattern on the wafer surface. If the wafers are already mechanically notched, alignment to the cut edges is preferred to overcome the saw tolerance and alignment errors. The various segmented cutting profiles may be preprogrammed into the tool path file or other positioning system command files.

[00144] Laser system 10 can be employed to produce one or more groups of small through holes, such as by laser punching using the laser parameters set forth above. These through holes can be positioned on the top side near the periphery (such as cut in from the

edges) of workpieces 12, circuits or dies, or within scribing, slicing, or dicing streets or their intersections such that the back or bottom side of workpiece 12 can be precisely aligned to with respect to features on the top side. These marks can also be made in chuck top 104 or in a retaining carrier 106 carrier such as a tape frame on which the workpiece 12 is mounted.

[00145] Such alignment facilitates backside processing such as laser scribing or sawing to enhance processing speed or quality. It is well known that laser cutting rate decreases with increasing depth into the wafer. As such, cutting from both sides would allow faster cutting of the wafer, since two half thickness cuts are faster than one cut of the full thickness. Two lasers could also be used simultaneously to cut the same or different dice lanes for increased throughput. This technique would also allow for cuts to be made through thicker materials, where half the thickness is below the saturation depth, but the full thickness is too deep to cut due to saturation. Another advantage of backside processing includes the ability to use a more pristine cutting technique on the device side of the wafer, while using a more aggressive technique to cut at higher speed from the backside without compromising the devices. The cutting from both sides can be accomplished either by the use of a laser system 10 which has laser beams impinging on the workpiece 12 from both sides such as shown in FIG. 1C, or by flipping the workpiece 12 in order to expose both sides to the laser output in succession.

[00146] Techniques for front and/or backside wafer slicing or dicing are discussed in more detail in U.S. Patent Application No. 09/803,382 ('382 Application) of Fahey et al., entitled "UV Laser Cutting or Shape Modification of Brittle, High Melting Temperature Target Materials such as Ceramics or Glasses, which is incorporated herein by reference. This information was published on March 21, 2002 under U.S. Patent Publication No. US-2001-0033558 and published on March 28, 2002 under International Patent Publication No. WO 02/24396, which correspond to the '382 Application.

[00147] Another application of the segment cutting method is to produce MEMS (microelectronic machine system) devices 160. FIG. 25 is a representative illustration of ultraviolet laser cutting of a MEMS device 160. In one preferred embodiment, the MEMS device 160 is cut using the method described above to create trenches 162a, 162b, 162c, 162d, and 162e (generically trenches 162) in silicon and to create a depression 164 by employing a pattern of adjacent trenches 162. Skilled persons will appreciate that through computer control of the X and/or Y axes of the laser positioning system 30, the directed laser system output pulses 32 can be directed to the work surface such that overlapped pulses create a pattern which expresses any complex curvilinear geometry. Skilled persons will

appreciate that the segmented cutting techniques and other processing techniques disclosed herein can be used to cut arcs and other curves for nonMEMS applications as well.

[00148] Another application of the segmented cutting method is to process optical integrated circuits, such as an arrayed waveguide gratings (AWG) device 170 produced on semiconductor wafer workpieces 12. FIG. 26 is a representative illustration of ultraviolet ablative patterning of an AWG device 170. In one preferred embodiment, the AWG 170 is patterned using the method described above to create curvilinear trenches 132, with portions 172a, 172b, 172c, 172d, and 172e in silicon, for example. Although trench 172 is shown to be symmetric, skilled persons will appreciate that through computer control of the X and/or Y axes of the laser positioning system 30, the directed laser system output pulses 32 can be directed to the work surface such that overlapped pulses 32 create a pattern which expresses any complex curvilinear profile or geometry. Skilled persons will appreciate that segments 122 are not required to be linear and can be arcs such that each portion 172 can be processed with one or more non linear segments 122. This capability may be used to produce complex curvilinear geometric patterns in silicon useful for efficient production of a variety of AWG devices 170. Skilled persons will also appreciate that the segmented cutting techniques could be employed to produce large diameter through hole or blind vias.

[00149] It is contemplated that performing the cuts in a reactive gas atmosphere, such as an oxygen-rich atmosphere, will generate debris that is easier to cut. To the extent that redep (or exposed trench material) cooling or resolidification is a factor, a recharacterization time interval may to some extent influence the maximum preferred length 126 of segments 122 such that the laser spot can process length 126 and return to impinge again any redep (or warmed exposed trench material) at the initial laser target position 132a and subsequent target positions 132 before the redep (or exposed trench material) cools or sticks strongly.

[00150] Skilled persons will also appreciate that purge gases, such as nitrogen, argon, helium, and dry air, may be usefully employed to assist in the removal of waste fumes from the workpiece 12 and more preferably to blow potential backfill through any existing throuchcut portions along cutting path 112. Such purge gases can be delivered to the close vicinity of the work surface using delivery nozzles attached to laser system 10.

[00151] If desirable, silicon workpieces 12 processed in accordance with the present invention may be cleaned using ultrasonic baths in liquids including but not limited to water, acetone, methanol, and ethanol to improve the surface quality of affected areas. Those

skilled in the art will also recognize that cleaning of processed silicon workpieces 12 in hydrofluoric acid can be beneficial in removing unwanted oxide layers.

[00152] It will be obvious to those having skill in the art that many changes may be made to the details of the above-described embodiments of this invention without departing from the underlying principles thereof. The scope of the present invention should, therefore, be determined only by the following claims.

Claims

1. A method for cutting a workpiece having a substrate supporting a layer, the substrate having a wafer material and the layer having a material different from that of the substrate, comprising:

applying a first technique to form a first kerf in the layer, the first technique including directing a first laser output having a first set of first parameters along a cutting path across the layer to form the kerf in the layer; and

applying along the first cutting path a second technique to form a second kerf in the substrate that underlies at least a portion of the first kerf, the second technique being different from the first technique.

2. The method of claim 1 in which the second technique employs a cutting blade.

3. The method of claim 1 in which the second technique further comprises directing a second laser output having a second set of second parameters, in which at least one of the second parameters has a second value that is substantially different from a first value of a corresponding first parameter.

4. The method of claim 3 in which the value comprises a wavelength value.

5. The method of claim 3 in which the value comprises an irradiance value.

6. The method of claim 3 in which the value comprises a repetition rate value.

7. The method of claim 3 in which the value comprises a bite size value.

8. The method of claim 3 in which the value comprises a scan speed value.

9. The method of claim 3 in which the value comprises a laser pass overlap value.

10. The method of claim 3 in which the value comprises a repetition rate value.

11. The method of claim 3 in which the value comprises a bite size value.

12. The method of claim 3 in which the second parameters have at least three value that are substantially different from respective values of the corresponding first parameters.

13. The method of claim 3 in which the first laser output is generated by a first laser and the second laser output is generated by a second laser that is of a different type than that of the first laser.

14. The method of claim 13 in which the first laser is a UV or visible laser and the second laser is an IR laser or visible laser.

15. The method of claim 13 in which the first and second lasers are both UV lasers that generate output at different wavelengths.

16. The method of claim 3 in which the first and second lasers are UV lasers that generate output at the same wavelength.

17. The method claim 3 in which the first and second laser-outputs are generated by the same laser.

18. The method of claim 3 in which the substrate comprises: Si, GaAs, GaP, InP, sapphire, SiGe, silicon on sapphire, silicon carbide, silicon on insulator, AlTiC, alumina, or other ceramic material.

19. The method of claim 1 in which the substrate comprises: Si, GaAs, GaP, InP, sapphire, SiGe, silicon on sapphire, silicon carbide, silicon on insulator, AlTiC, alumina, or other ceramic material.

20. The method of claim 19 in which the layer comprises: a metal, an oxide, a nitride, a polymer, an epitaxial or amorphous or polycrystalline semiconductor material, a low-K dielectric material, a photoresist, PVA, silicon dioxide, or silicon nitride.

21. The method of claim 1 in which the layer comprises: a metal, an oxide, a nitride, a polymer, an epitaxial or amorphous or polycrystalline semiconductor material, a low-K dielectric material, a photoresist, PVA, silicon dioxide, or silicon nitride.

22. The method of claim 3 in which the layer comprises silicon dioxide, the substrate comprises silicon, the first laser output includes a lower intensity at a high scan speed, and the second laser output includes a higher intensity.

23. The method of claim 2 in which the cutting blade has width, the layer includes a material that adversely affects durability of the cutting blade, and the first kerf is wider than the width of the cutting blade.

24. The method of claim 3 in which the first or second laser comprises an excimer, CO_2, Nd:YAG, Nd:YLF, Nd:vanadate, Yb:YAG, Yb-doped fiber, Ar-Ion, or Cu vapor laser.

25. The method of claim 1 in which the first laser comprises an excimer, CO_2, Nd:YAG, Nd:YLF, Nd:vanadate, Yb:YAG, Yb-doped fiber, Ar-Ion, or Cu vapor laser.

26. The method of claim 1 in which the layer constitutes a first layer and the workpiece comprises a second layer positioned between the first layer and the substrate, wherein the second layer has a material different from that of the first layer and different from that of the susbstrate.

27. The method of claim 26 further comprising:

applying along the first cutting path a third technique to form a third kerf in the second layer that underlies at least a portion of the first kerf, the third technique being different from the first technique.

28. The method of claim 27 in which the third technique further comprises directing a second laser output having a second set of second parameters, in which at least one of the second parameters has a second value that is substantially different from a first value of a corresponding first parameter.

29. The method of claim 28 in which the second technique employs a cutting blade.

30. The method of claim 3 in which the second laser output is applied at a bite size of 0.5-9 μm.

31. The method of claim 1 in which the second laser output is applied at a bite size of 0.5-9 μm.

32. The method of claim 23 in which the first laser output is applied in multiple at least partly overlapping parallel passes to achieve a desired kerf width.

33. The method of claim 3 in which the second laser output is applied in multiple at least partly overlapping parallel passes to achieve a desired kerf width.

34. The method of claim 1 in which the workpiece has first and second opposite sides and the first technique is applied on the first side and the second technique is applied from the second side.

35. The method of claim 1 further comprising applying a fourth technique to a corner formed by either the first or second technique, the fourth technique including directing a fourth laser output having a fourth set of fourth parameters at or in proximity to the corner to round it.

36. The method of claim 3 in which the first or second laser outputs have propagated through a beam shaping element.

37. The method of claim 1 in which the second technique forms a throughcut in the workpiece.

38. The method of claim 3 in which the second technique forms a throughcut in the workpiece.

39. The method of claim 13 in which the second technique forms a throughcut in the workpiece.

40. The method of claim 18 in which the second technique forms a throughcut in the workpiece.

41. The method of claim 3 in which the second laser output is applied using a segmented cutting technique.

42. The method of claim 3 in which the second laser output is applied to form a snapstrate.

43. The method of claim 3 in which the first and second kerfs are substantially circular such that the first and second techniques are applied to form a large diameter via in the workpiece.

44. The method of claim 1 in which the workpiece has first and second opposite sides and the first and second techniques are applied to both sides.

45. A method for cutting a workpiece having a substrate supporting a layer, the substrate having a wafer material and the layer having a material different from that of the substrate and prone to propagating cracks that initiate during a cutting technique, comprising:

applying a first technique to form a first kerf through the layer along a first cutting path, the first technique including directing a first laser output having a first set of first parameters along a cutting path across the layer to form the kerf through the layer and the first parameters adapted to minimize initiation of cracks; and

applying along a second cutting path parallel to the first cutting path a second technique to form a second kerf in the substrate parallel to the first kerf, the second technique being different from the first technique and the second technique initiating cracks in the layer that begin at the second kerf, propagate in a direction toward the first kerf, and terminate at or prior to the first kerf.

46. The method of claim 45, further comprising:

prior to applying the second cutting technique, applying the first technique, or a minor variation thereof, to form a third kerf through the layer along a third cutting path that is parallel to the first kerf, and

applying the second cutting technique such that the second kerf is formed between the first and third kerfs and such that the second technique initiates cracks in the layer that begin at the second kerf, propagate in a direction toward the third kerf, and terminate at or prior to the third kerf.

47. The method of claim 46 in which the second technique employs a cutting blade.

48. The method of claim 46 in which the second technique further comprises directing a second laser output having a second set of second parameters, in which at least

one of the second parameters has a second value that is substantially different from a first value of a corresponding first parameter.

49. The method of claim 48 in which the value comprises a wavelength value.

50. The method of claim 48 in which the value comprises an irradiance value.

51. The method of claim 48 in which the value comprises a repetition rate value.

52. The method of claim 48 in which the value comprises a bite size value.

53. The method of claim 48 in which the value comprises a scan speed value.

54. The method of claim 48 in which the value comprises a laser pass overlap value.

55. The method of claim 48 in which the value comprises a repetition rate value.

56. The method of claim 48 in which the value comprises a bite size value.

57. The method of claim 48 in which the second parameters have at least three value that are substantially different from respective values of the corresponding first parameters

58. The method of claim 48 in which the first laser output is generated by a first laser and the second laser output is generated by a second laser that is of a different type than that of the first laser.

59. The method of claim 58 in which the first laser is a UV or visible laser and the second laser is an IR laser.

60. The method of claim 58 in which the first and second lasers are both UV lasers that generate output at different wavelengths.

61. The method of claim 46 in which the substrate comprises: Si, GaAs, GaP, InP, sapphire, SiGe, silicon on sapphire, silicon carbide, silicon on insulator, AlTiC, alumina, or other ceramic material.

62. The method of claim 61 in which the layer comprises: a metal, an oxide, a nitride, a polymer, an epitaxial or amorphous or polycrystalline semiconductor material, a low-K dielectric material, a photoresist, PVA, silicon dioxide, or silicon nitride.

63. The method of claim 48 in which the layer comprises silicon dioxide, the substrate comprises silicon, the first laser output includes a lower intensity at a high scan speed, and the second laser output includes a higher intensity.

64. The method of claim 48 in which the first or second laser comprises an excimer, CO_2, Nd:YAG, Nd:YLF, Nd:vanadate, Yb:YAG, Yb-doped fiber, Ar-Ion, or Cu vapor laser.

65. The method of claim 46 in which the first laser comprises an excimer, CO_2, Nd:YAG, Nd:YLF, Nd:vanadate, Yb:YAG, Yb-doped fiber, Ar-Ion, or Cu vapor laser.

66. The method of claim 46 in which the layer constitutes a first layer and the workpiece comprises a second layer positioned between the first layer and the substrate, wherein the second layer has a material different from that of the first layer and different form that of the susbstrate.

67. The method of claim 66 further comprising:

applying along the first cutting path a third technique to form a third kerf in the second layer that underlies at least a portion of the first kerf, the third technique being different from the first technique.

68. The method of claim 67 in which the third technique further comprises directing a second laser output having a second set of second parameters, in which at least one of the second parameters has a second value that is substantially different from a first value of a corresponding first parameter.

69. The method of claim 46 in which the second technique employs a cutting blade.

70. The method of claim 48 in which the second laser output is applied at a bite size of 0.5-9 μm.

71. The method of claim 46 in which the first laser output is applied at a bite size of 0.5-9 μm

72. The method of claim 46 in which the second technique forms a throughcut in the workpiece.

73. The method of claim 48 in which the second technique forms a throughcut in the workpiece.

74. The method of claim 48 in which the second laser output is applied using a segmented cutting technique.

75. The method of claim 46 in which the second laser output is applied to form a snapstrate.

76. A method for cutting a workpiece having a substrate supporting a layer, the substrate having a wafer material and the layer having a material different from that of the substrate and having a tendency to delaminate from the substrate at or near a layer-substrate interface during a cutting technique, comprising:

applying a first technique to form a first kerf through the layer along a first cutting path, the first technique including directing a first laser output having a first set of first

parameters along the first cutting path across the layer to form the kerf through the layer and the first parameters adapted to minimize initiation of delamination of the layer from the susbstrate; and

applying along the first cutting path a second technique to form a second kerf in the substrate that underlies at least a portion of the first kerf, the second technique including directing a second laser output having a second set of second parameters along the first cutting path across the susbtrate to form the kerf partly through the susbstrate and the second parameters adapted to minimize initiation of delamination of the layer from the susbstrate; and

applying along a second cutting path parallel to the first cutting path a third technique to form a second kerf in the substrate parallel to the first kerf, the third technique being different from the first technique and the third technique initiating delamination of the layer from the substrate that begins at the second kerf, propagates in a direction toward the first kerf, and terminates at or prior to the first kerf.

77. The method of claim 76, further comprising:

prior to applying the second cutting technique, applying the first technique, or a minor variation thereof, to form a third kerf through the layer along a third cutting path that is parallel to the first kerf, and

applying the second cutting technique such that the second kerf is formed between the first and third kerfs and such that the second technique initiates cracks in the layer that begin at the second kerf, propagate in a direction toward the third kerf, and terminate at or prior to the third kerf.

78. The method of claim 77 in which the second technique employs a cutting blade.

79. The method of claim 77 in which the second technique further comprises directing a second laser output having a second set of second parameters, in which at least one of the second parameters has a second value that is substantially different from a first value of a corresponding first parameter.

80. The method of claim 79 in which the value comprises a wavelength value.

81. The method of claim 79 in which the value comprises an irradiance value.

82. The method of claim 79 in which the value comprises a repetition rate value.

83. The method of claim 79 in which the value comprises a bite size value.

84. The method of claim 79 in which the value comprises a scan speed value.

85. The method of claim 79 in which the value comprises a laser pass overlap value.

86. The method of claim 79 in which the value comprises a repetition rate value.

87. The method of claim 79 in which the value comprises a bite size value.

88. The method of claim 79 in which the second parameters have at least three value that are substantially different from respective values of the corresponding first parameters

89. The method of claim 79 in which the first laser output is generated by a first laser and the second laser output is generated by a second laser that is of a different type than that of the first laser.

90. The method of claim 89 in which the first laser is a UV or visible laser and the second laser is an IR laser.

91. The method of claim 89 in which the first and second lasers are both UV lasers that generate output at different wavelengths.

92. The method of claim 77 in which the substrate comprises: Si, GaAs, GaP, InP, sapphire, SiGe, silicon on sapphire, silicon carbide, silicon on insulator, AlTiC, alumina, or other ceramic material.

93. The method of claim 92 in which the layer comprises: a metal, an oxide, a nitride, a polymer, an epitaxial or amorphous or polycrystalline semiconductor material, a low-K dielectric material, a photoresist, PVA, silicon dioxide, or silicon nitride.

94. The method of claim 79 in which the layer comprises silicon dioxide, the substrate comprises silicon, the first laser output includes a lower intensity at a high scan speed, and the second laser output includes a higher intensity.

95. The method of claim 79 in which the first or second laser comprises an excimer, CO_2, Nd:YAG, Nd:YLF, Nd:vanadate, Yb:YAG, Yb-doped fiber, Ar-Ion, or Cu vapor laser.

96. The method of claim 77 in which the first laser comprises an excimer, CO_2, Nd:YAG, Nd:YLF, Nd:vanadate, Yb:YAG, Yb-doped fiber, Ar-Ion, or Cu vapor laser.

97. The method of claim 77 in which the layer constitutes a first layer and the workpiece comprises a second layer positioned between the first layer and the substrate, wherein the second layer has a material different from that of the first layer and different form that of the susbstrate.

98. The method of claim 97 further comprising:

applying along the first cutting path a third technique to form a third kerf in the second layer that underlies at least a portion of the first kerf, the third technique being different from the first technique.

99. The method of claim 98 in which the third technique further comprises directing a second laser output having a second set of second parameters, in which at least one of the second parameters has a second value that is substantially different from a first value of a corresponding first parameter.

100. The method of claim 77 in which the second technique employs a cutting blade.

101. The method of claim 79 in which the second laser output is applied at a bite size of 0.5-9 μm.

102. The method of claim 77 in which the first laser output is applied at a bite size of 0.5-9 μm

103. The method of claim 77 in which the second technique forms a throughcut in the workpiece.

104. The method of claim 79 in which the second technique forms a throughcut in the workpiece.

105. The method of claim 77 in which the second laser output is applied using a segmented cutting technique.

106. The method of claim 77 in which the second laser output is applied to form a snapstrate.

FIG. 1A

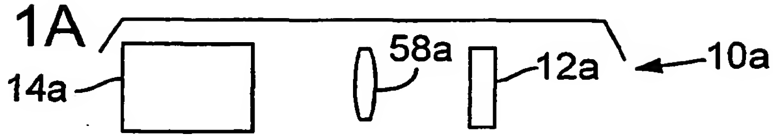


FIG. 1B

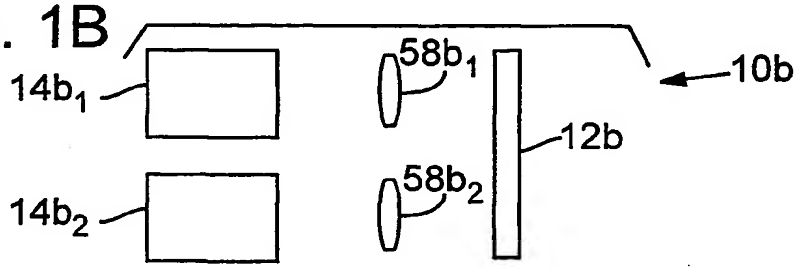


FIG. 1C

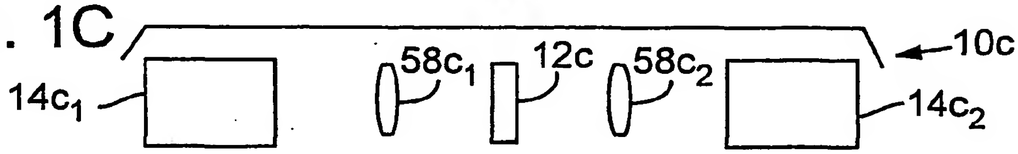


FIG. 1D

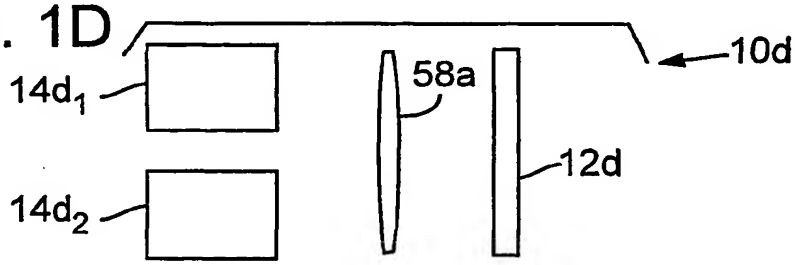


FIG. 1E

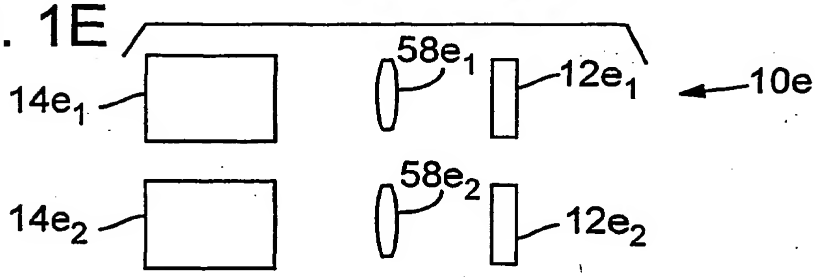
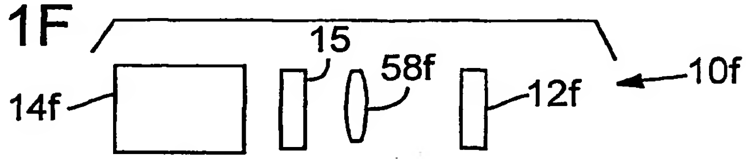
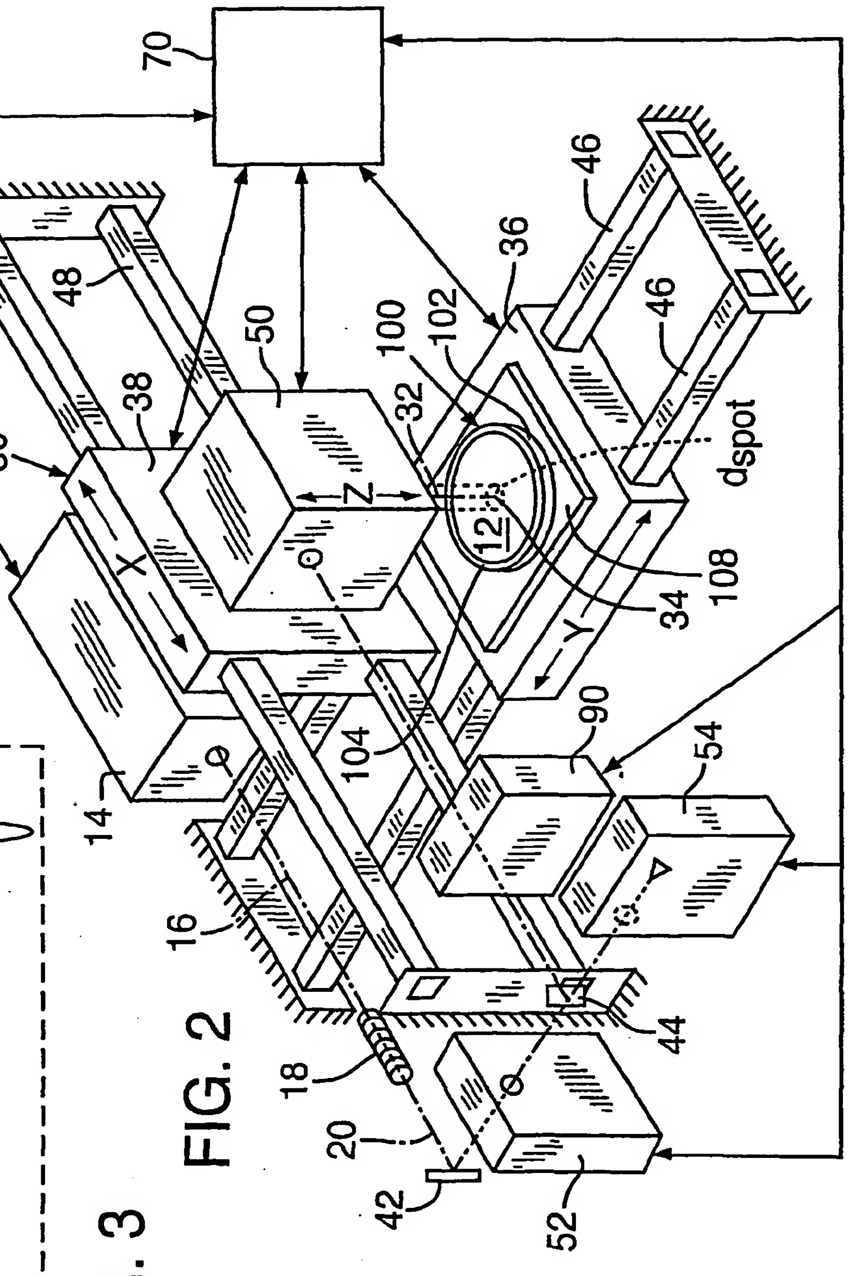


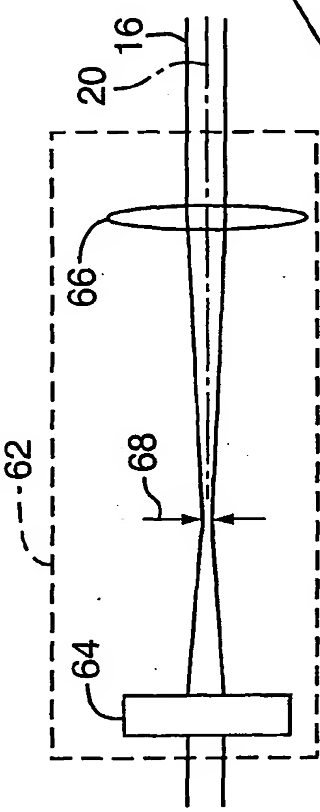
FIG. 1F





70
10a
30
38
50
48
48
36
46
46
100
102
32
Z
X
12
dspot
34
108
Y
14
104
90
54
16
18
44
20
42
52

FIG. 2



16
20
66
62
68
64

FIG. 3

FIG. 4

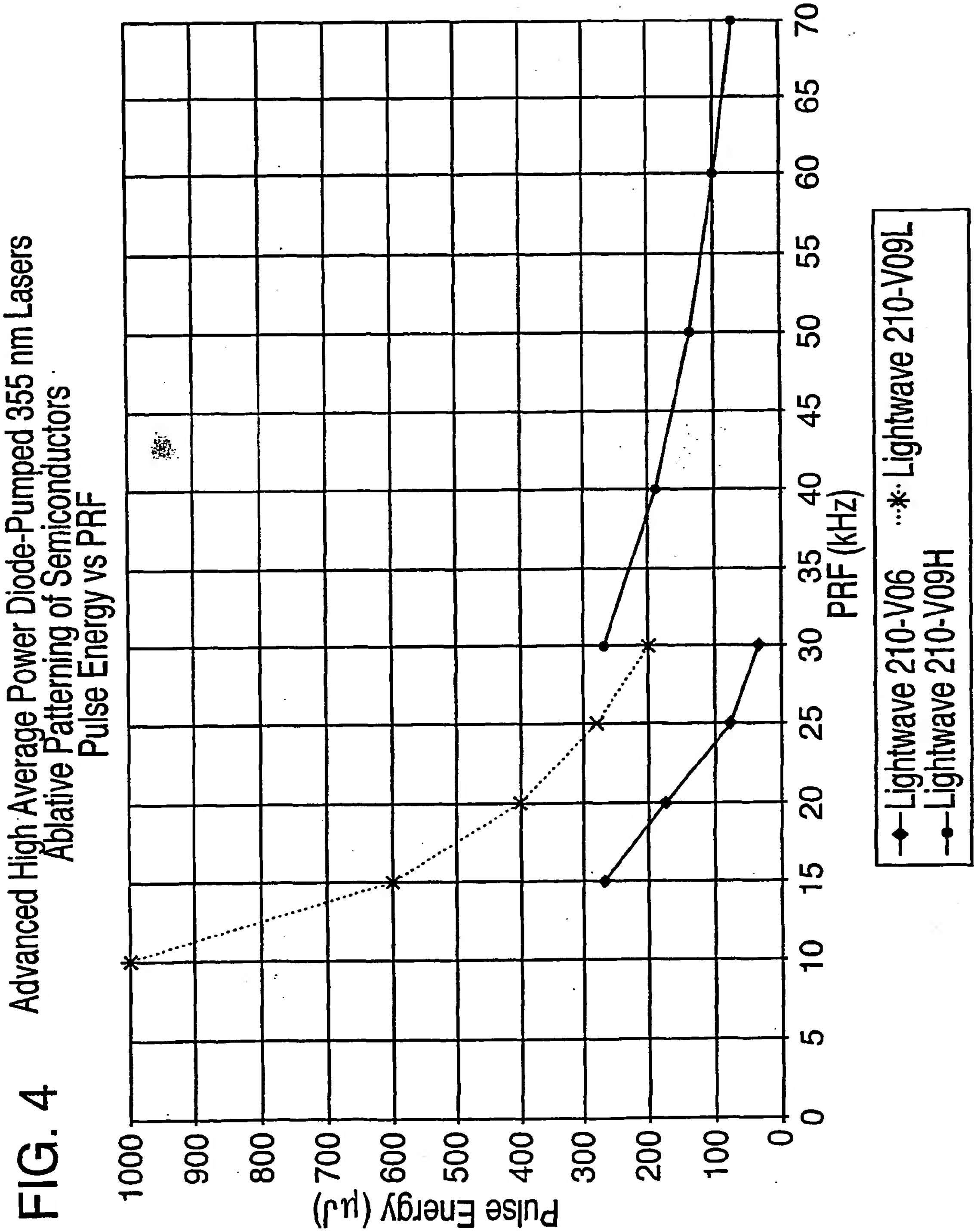

Advanced High Average Power Diode-Pumped 355 nm Lasers
Ablative Patterning of Semiconductors
Pulse Energy vs PRF
Pulse Energy (μJ)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
PRF (kHz)
Lightwave 210-V06
Lightwave 210-V09L
Lightwave 210-V09H

FIG. 5

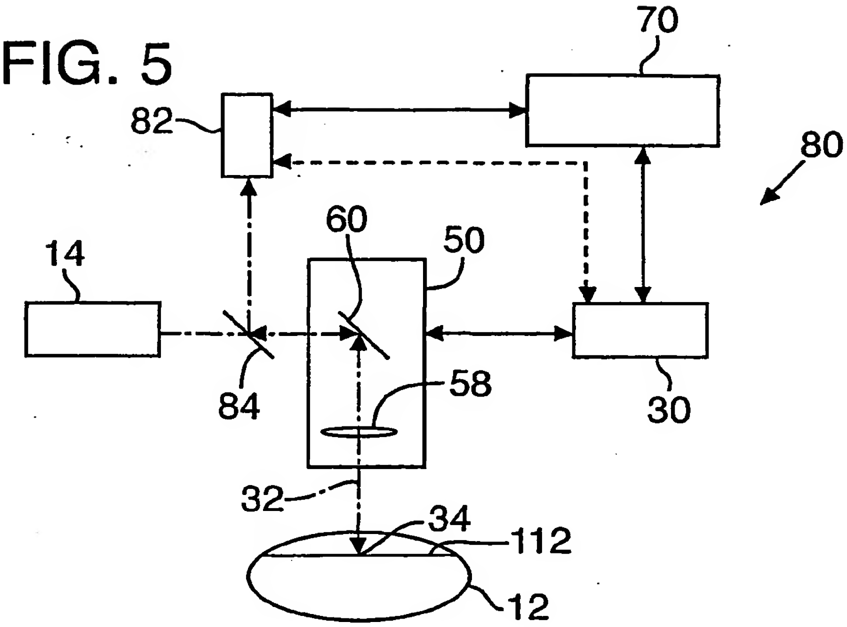
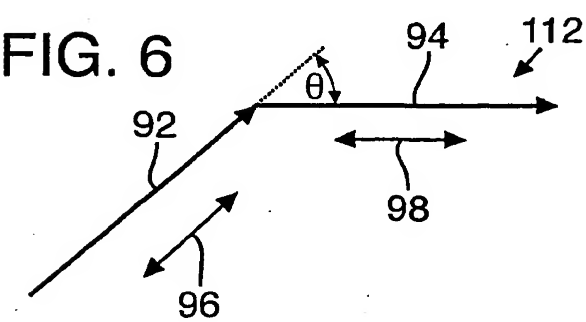


FIG. 6



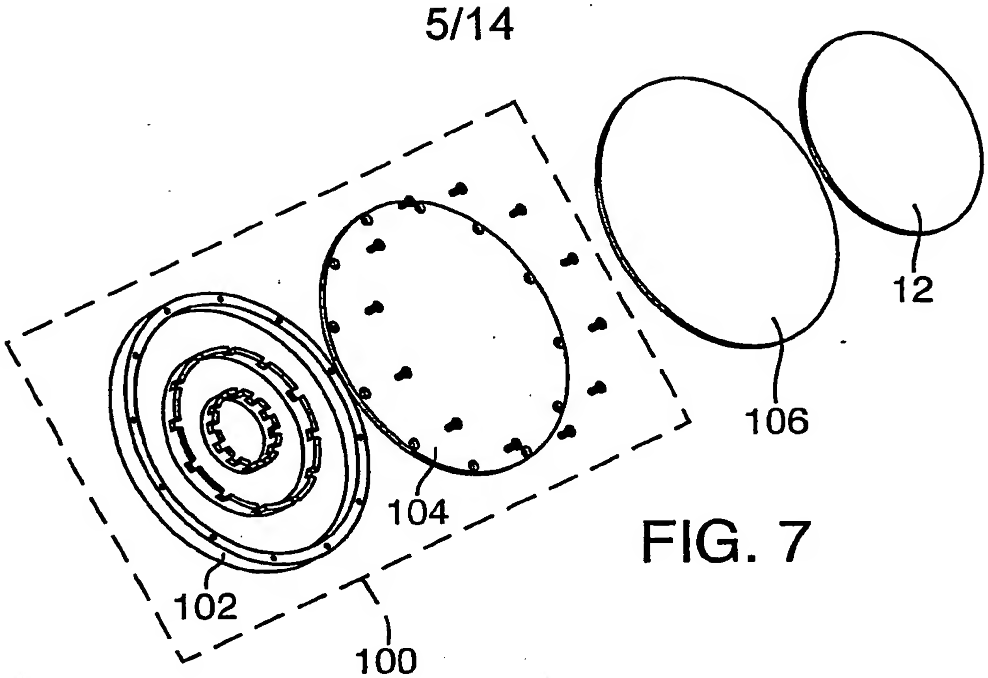


FIG. 7

FIG. 8

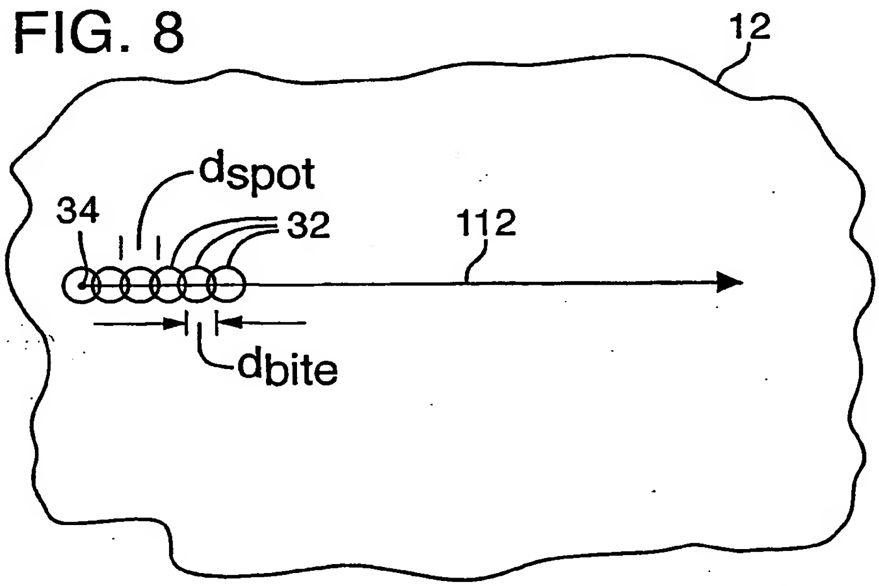


FIG. 9A

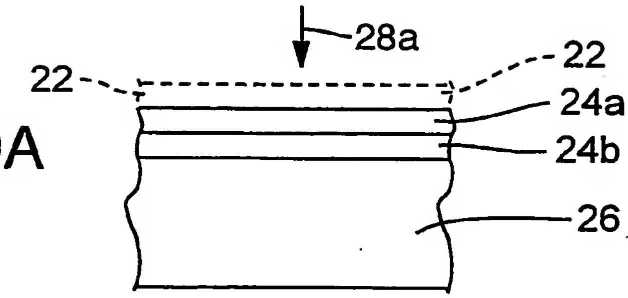


FIG. 9B

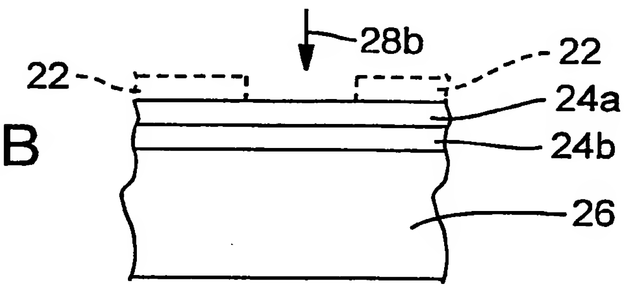


FIG. 9D

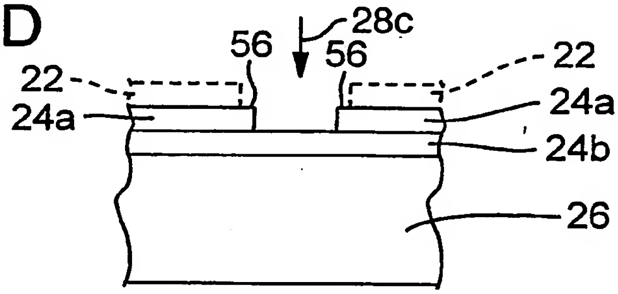


FIG. 9D

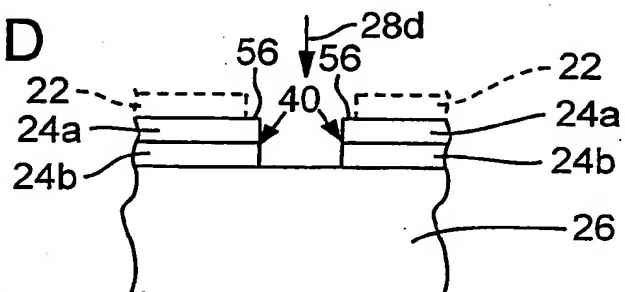


FIG. 9E

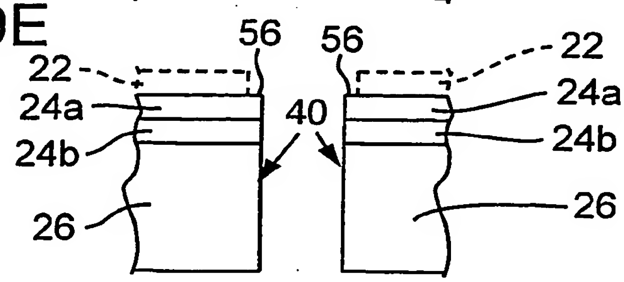


FIG. 10A

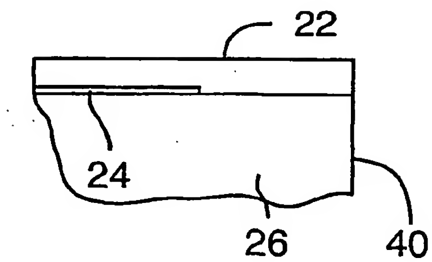


FIG. 10B

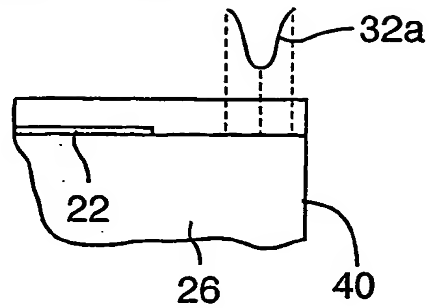


FIG. 10C

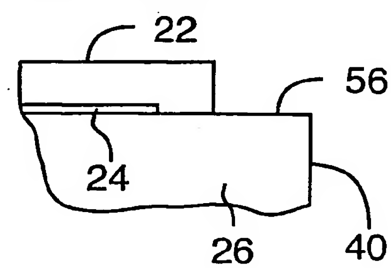


FIG. 10D

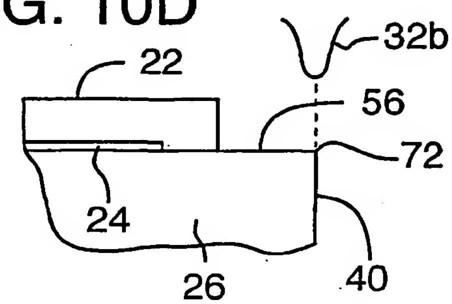


FIG. 10E

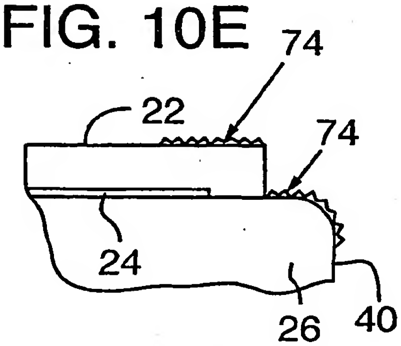


FIG. 10F

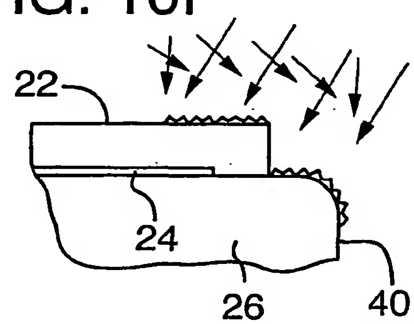


FIG. 10G

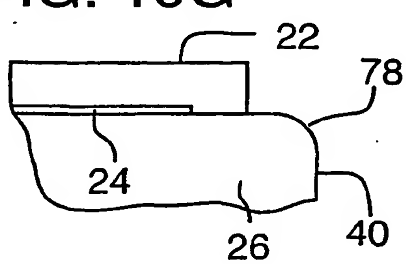
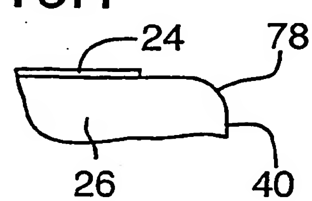


FIG. 10H



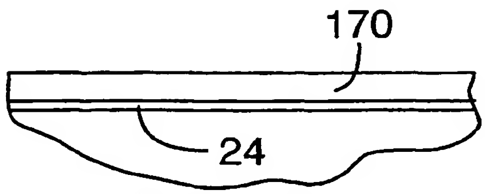


FIG. 11A

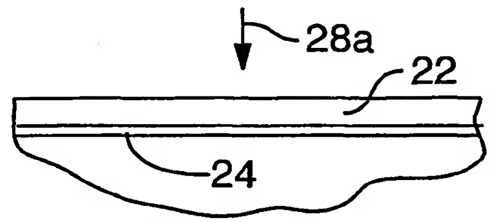


FIG. 11B

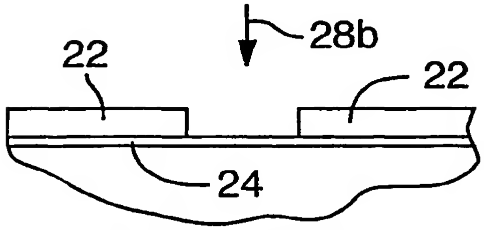


FIG. 11C

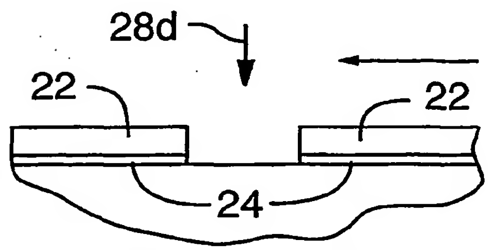


FIG. 11D

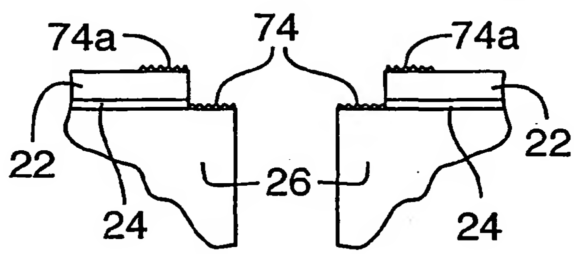


FIG. 11E

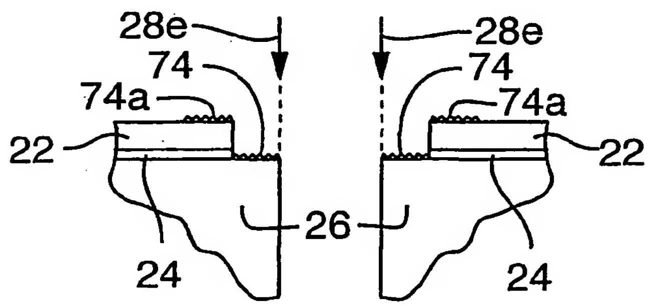


FIG. 11F

FIG. 12

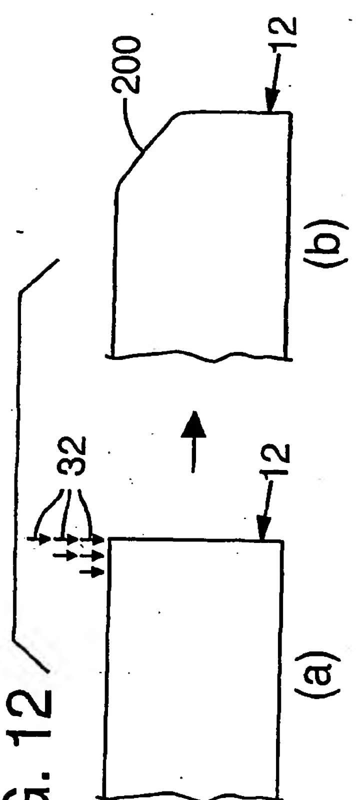


FIG. 14

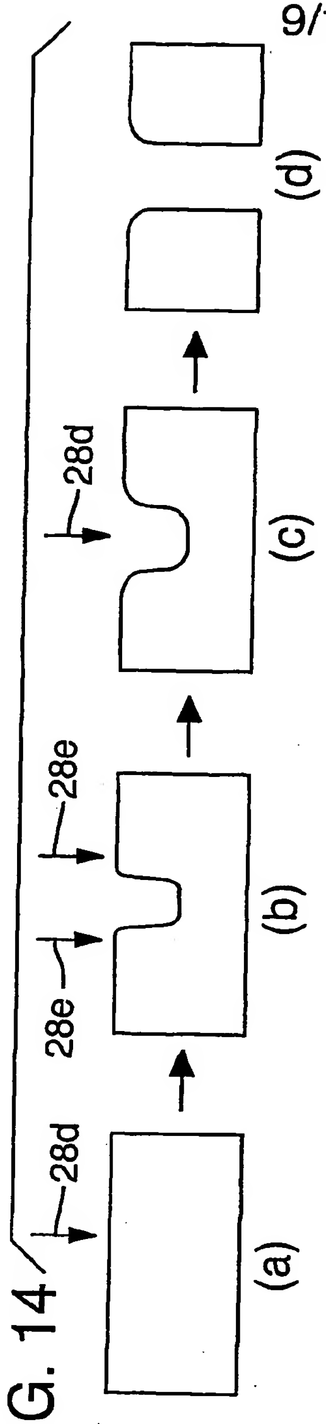


FIG. 15

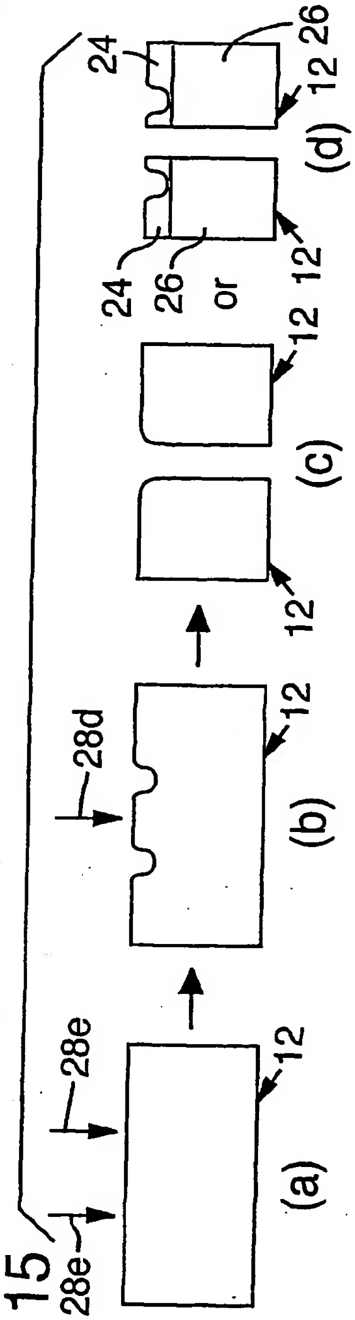


FIG. 13

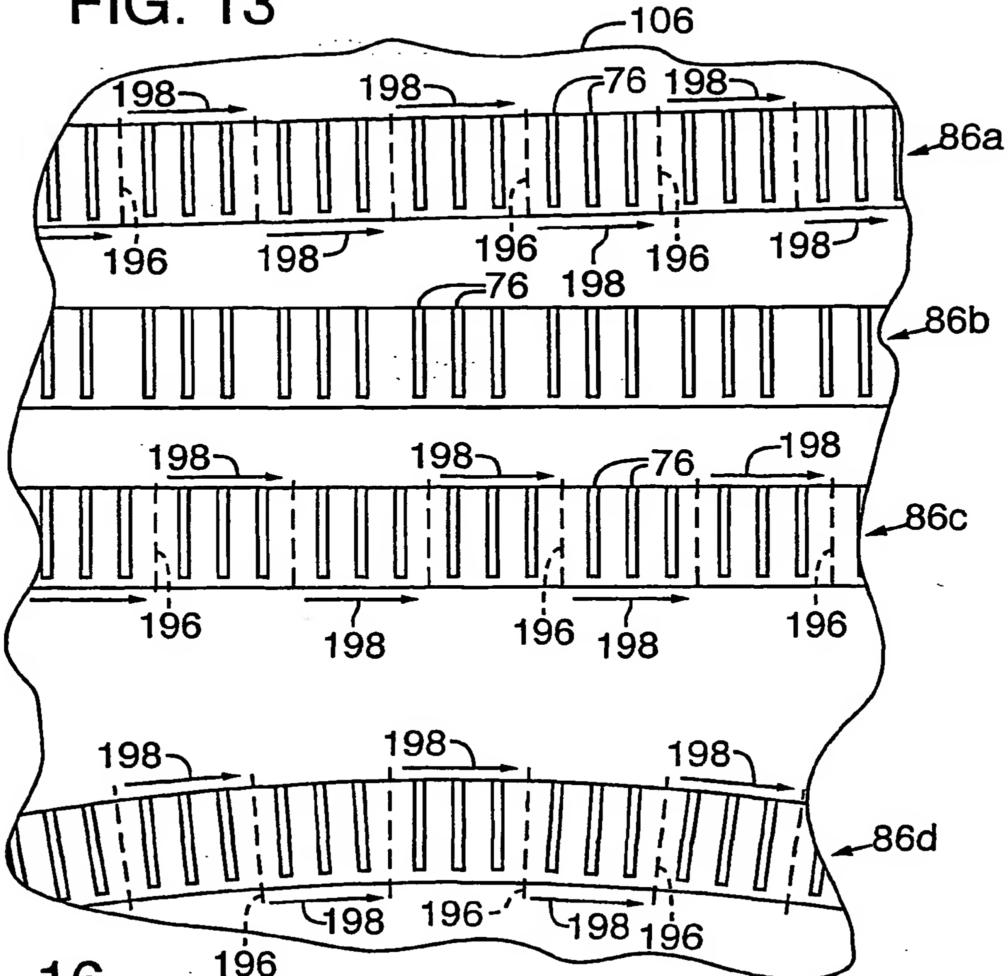


FIG. 16

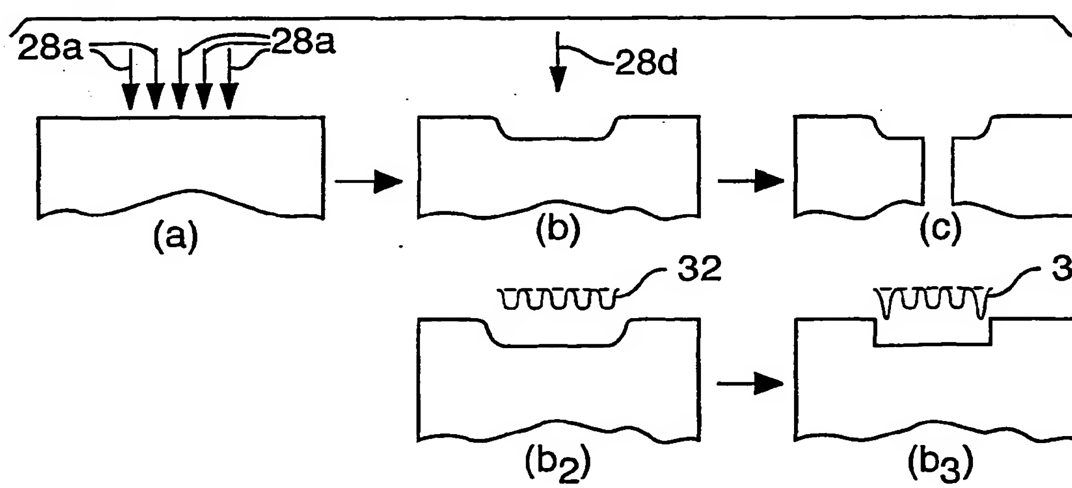


FIG. 17

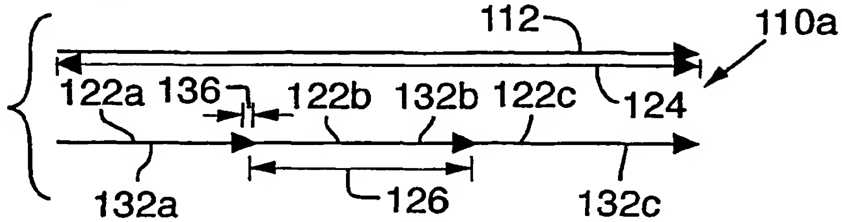


FIG. 18

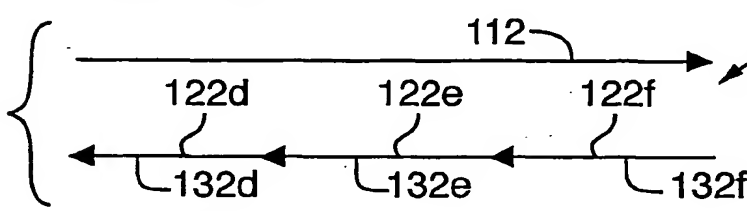


FIG. 19

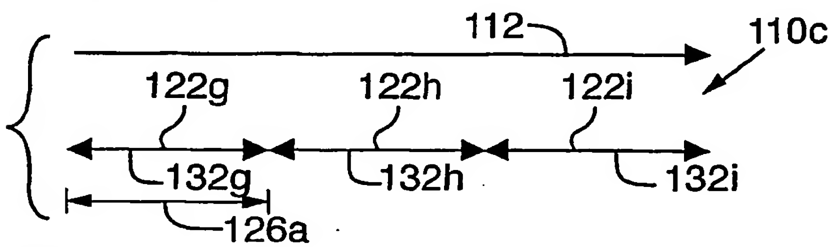


FIG. 20

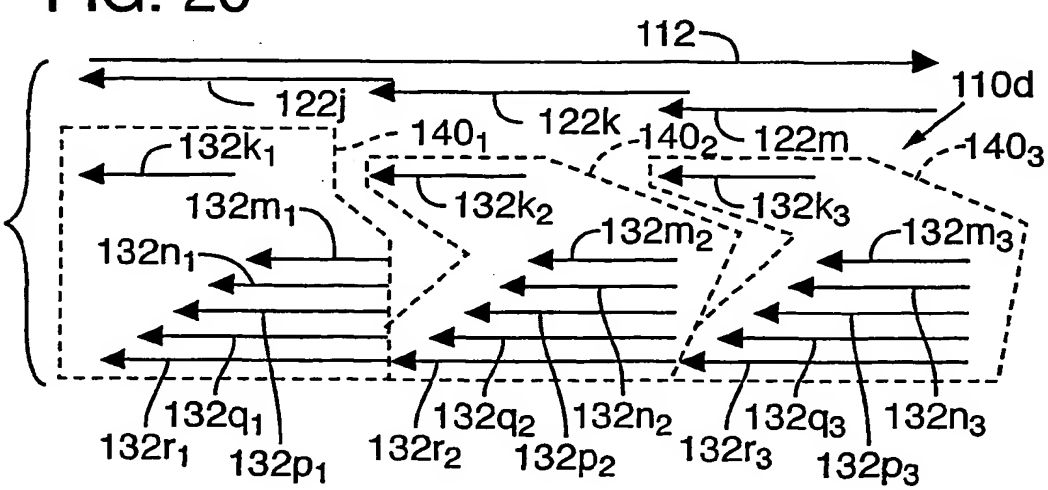


FIG. 21

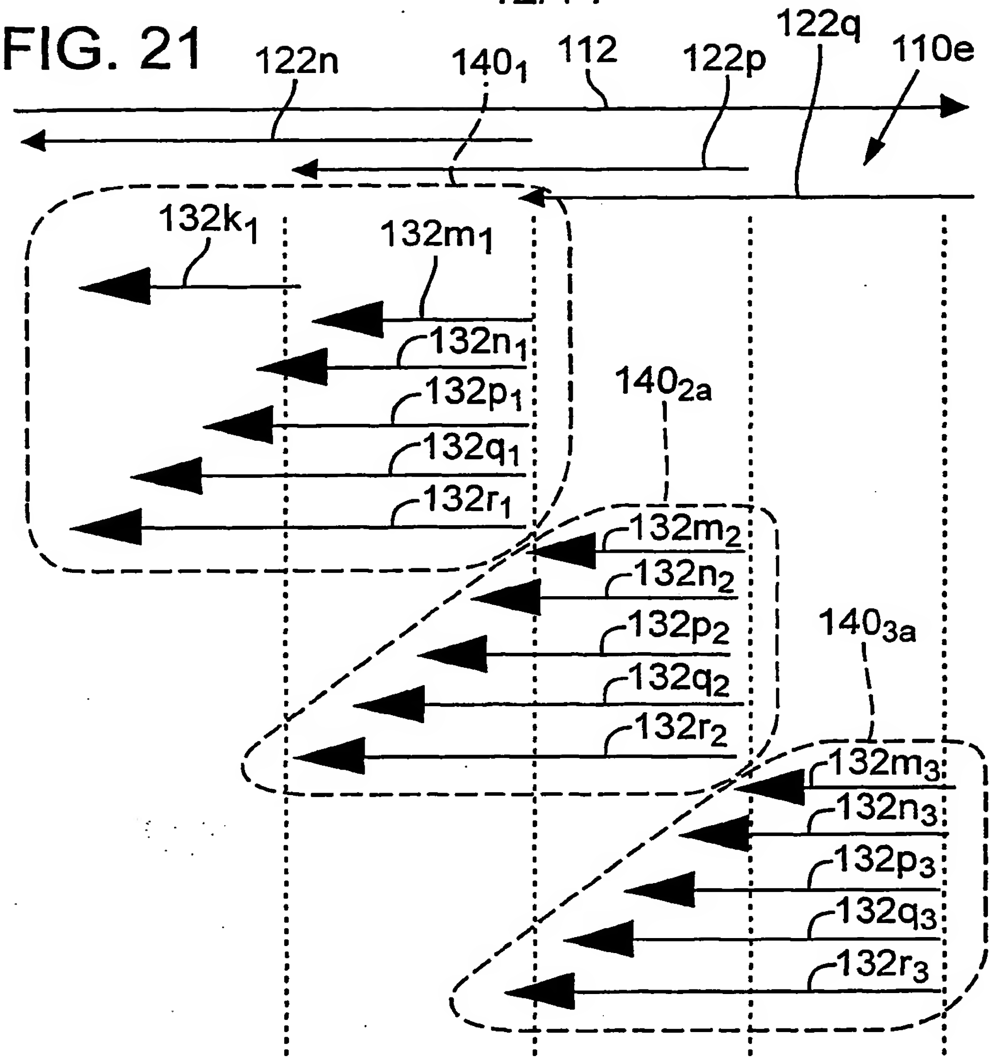


FIG. 22

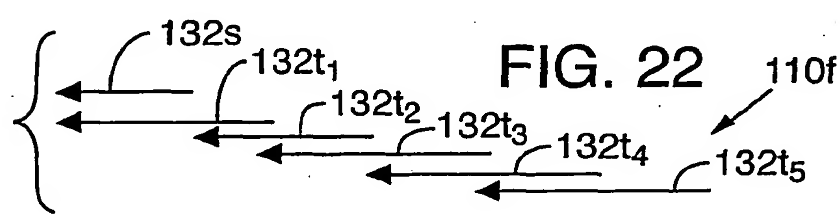


FIG. 23

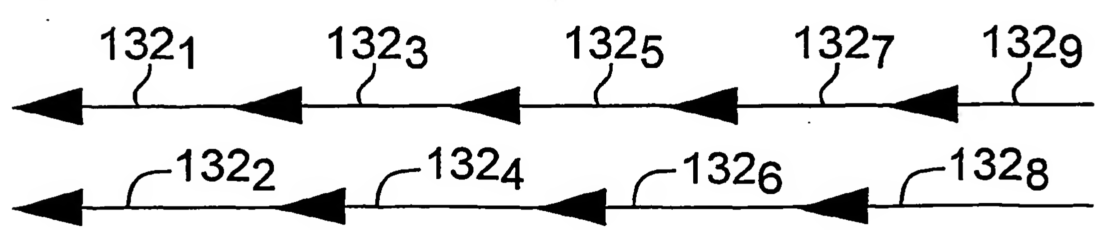
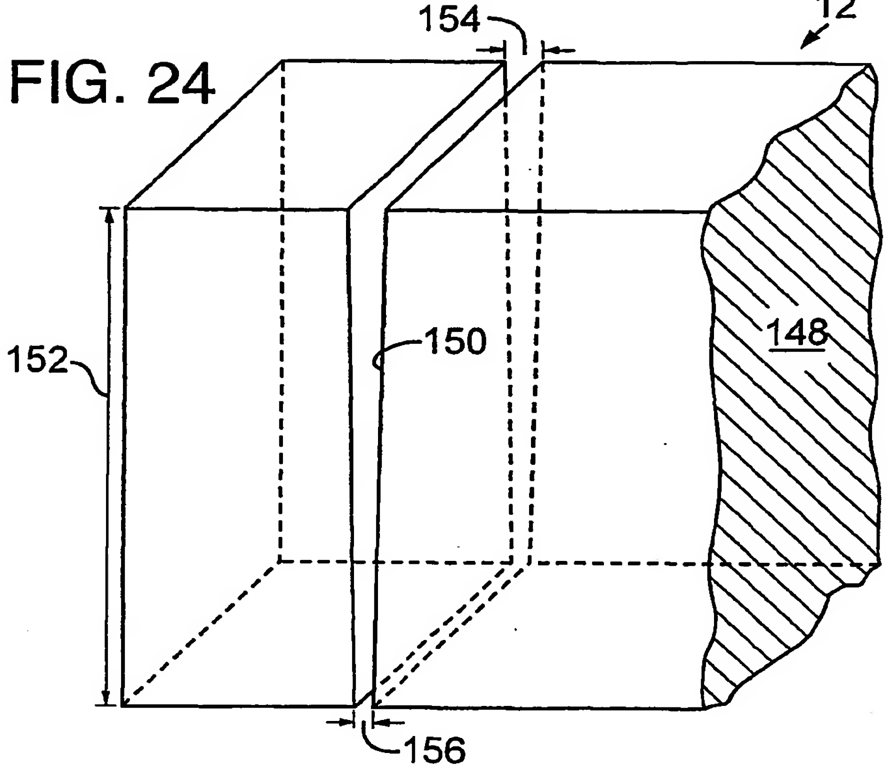


FIG. 24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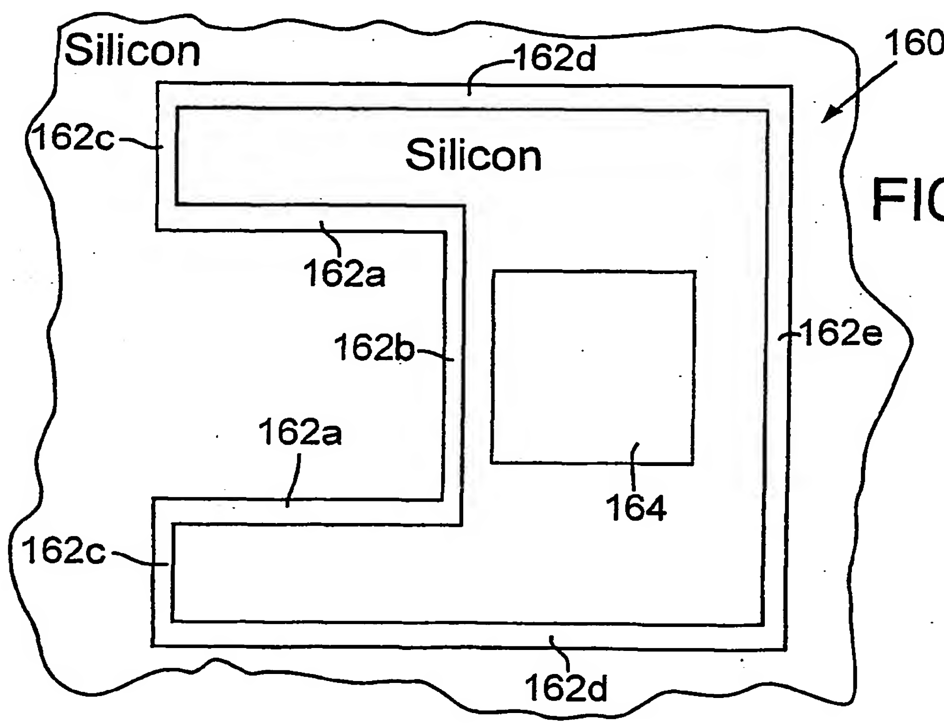
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162a
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162d

FIG. 25

FIG. 26